The Telescope Array and its prospects

Hiroyuki Sagawa (ICRR)
for the Telescope Array Collaboration

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Outline

- TA experiment (detector and operation)
- TA results
  - Spectrum (Hybrid / FD mono / SD)
  - Composition (p/Fe [FD stereo])
  - Anisotropy (SD)
    - LSS correlations / AGN correlations / auto-correlations
- Prospects (TALE / R&D@TA)
- Summary

The Telescope Array Collaboration

~120 researchers from Japan/US/Korea/Russia

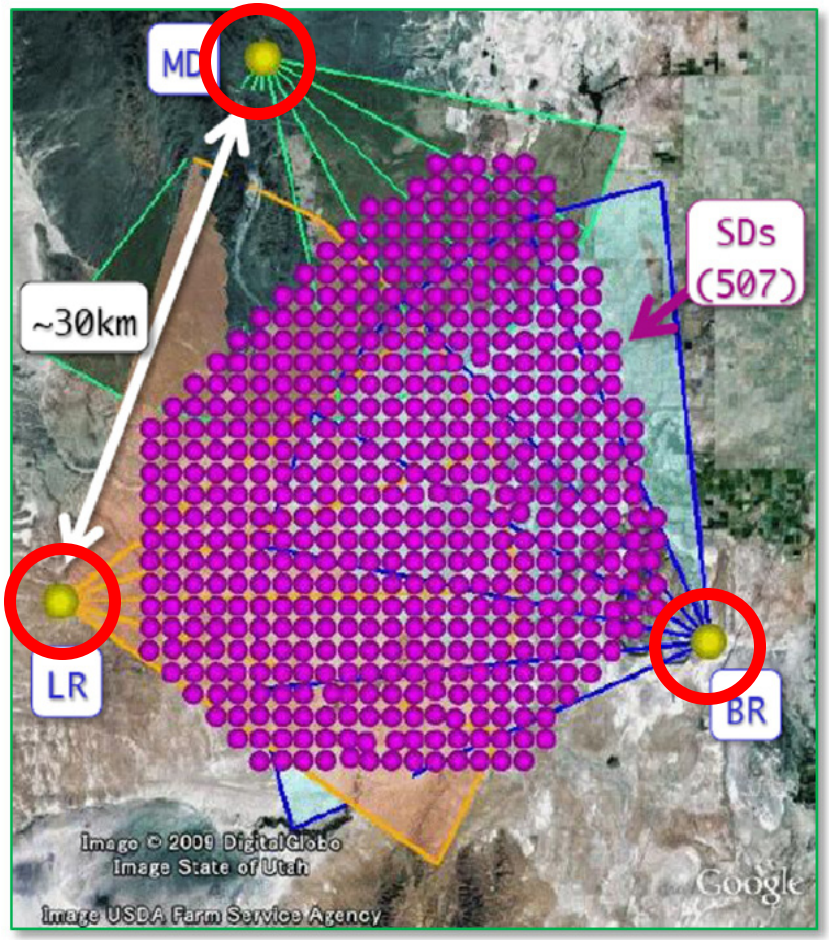
T. Abu-Zayyad[1], R. Aida[2], M. Allen[1], R. Azuma[3], E. Barcikowski[1], J.W. Belz[1],T. Benno[4], D.R. Bergman[5], S.A. Blake[1], O. Brusova[1], R. Cady[1], B.G. Cheon[6], J. Chiba[7], M. Chikawa[4], E.J. Cho[6], L.S. Cho[8], W.R. Cho[8], F. Cohen[9], K. Doura[4], C. Ebeling[1], H. Fujii[10], T. Fujii[11], T. Fukuda[3], M. Fukushima[9,22], D. Gorbunov[12], W. Hanlon[1], K. Hayashi[3], Y. Hayashi[11], N. Hayashida[9], K. Hibino[13],K. Hiyama[9], K. Honda[2], G. Hughes[5], T. Iguchi[3], D. Ikeda[9], K. Ikuta[2], S.J.J. Innemee[5], N. Inoue[14], T. Ishii[2], R. Ishimori[3], D. Ivanov[5], S. Iwamoto[2], C.C.H. Jui[1], K. Kadota[15], F. Kakimoto[3], O. Kalashev[12], T. Kanbe[2], H. Kang[16], K. Kasahara[17], H. Kawai[18], S. Kawakami[11], S. Kawana[14], E. Kido[9], B.G. Kim[19],H.B. Kim[6], J.H. Kim[6], J.H. Kim[20], A. Kitsugi[9], K. Kobayashi[7], H. Koers[21], Y. Kondo[9], V. Kuzmin[12], Y.J. Kwon[8], J.H. Lim[16], S.I. Lim[19], S. Machida[3], K. Martens[22], J. Martineau[1], T. Matsuda[10], T. Matsuyama[11], J.N. Matthews[1], M. Minamino[11], K. Miyata[7], H. Miyauchi[11], Y. Murano[3], T. Nakamura[23], S.W. Nam[19], T. Nonaka[9], S. Ogio[11], M. Ohnishi[9], H. Ohoka[9], T. Okuda[11], A. Oshima[11], S. Ozawa[17], I.H. Park[19], D. Rodriguez[1], S.Y. Roh[20], G. Rubtsov[12], D. Ryu[20], H. Sagawa[9],N. Sakurai[9], L.M. Scott[5], P.D. Shah[1], T. Shibata[9], H. Shimodaira[9], B.K. Shin[6], J.D. Smith[1], P. Sokolsky[1], T.J. Sonley[1], R.W. Springer[1], B.T. Stokes[5], S.R. Stratton[5], S. Suzuki[10], Y. Takahashi[9], M. Takeda[9], A. Taketa[9], M. Takita[9], Y. Tameda[3], H. Tanaka[11], K. Tanaka[24], M. Tanaka[10], J.R. Thomas[1], S.B. Thomas[1], T.A.Stroman[1], G.B. Thomson[5], P. Tinyakov[12,21], I. Tkachev[12], H. Tokuno[9], T. Tomida[2], R. Torii[9], S. Troitsky[12], Y. Tsunesada[3], Y. Tsuyuguchi[2], Y. Uchihori[25], S. Udo[13], H. Ukai[2], B. Van Klaveren[1], Y. Wada[14], M. Wood[1], T. Yamakawa[9], Y. Yamakawa[9], H. Yamaoka[10], J. Yang[19], S. Yoshida[18], H. Yoshii[26], Z. Zundel[1]

[1] *University of Utah, High Energy Astrophysics Institute, Salt Lake City, Utah, USA*
[2] *University of Yamanashi, Interdisciplinary Graduate School of Medicine and Engineering, Kofu, Yamanashi, Japan*
[3] *Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[4] *Kinki Unversity, Higashi Osaka, Osaka, Japan*
[5] *Rutgers University, Piscataway, USA*
[6] *Hanyang University, Seongdong-gu, Seoul, Korea*
[7] *Tokyo University of Science, Noda, Chiba, Japan*
[8] *Yonsei University, Seodaemun-gu, Seoul, Korea*
[9] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[10] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan*
[11] *Osaka City University, Osaka, Osaka, Japan*
[12] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[13] *Kanagawa University, Yokohama, Kanagawa, Japan*
[14] *Saitama University, Saitama, Saitama, Japan*
[15] *Tokyo City University, Setagaya-ku, Tokyo, Japan*
[16] *Pusan National University, GeumJeong-gu, Busan, Korea*
[17] *Waseda University, Advanced Research Institute for Science and Engineering, Shinjuku-ku, Tokyo, Japan*
[18] *Chiba University, Chiba, Chiba, Japan*
[19] *Ewha Womans University, Seodaaemun-gu, Seoul, Korea*
[20] *Chungnam National University, Yuseong-gu, Daejeon, Korea*
[21] *University Libre de Bruxelles, Brussels, Belgium*
[22] *University of Tokyo, Institute for the Physics and Mathematics of the Universe, Kashiwa, Chiba, Japan*
[23] *Kochi University, Kochi, Kochi, Japan*
[24] *Hiroshima City University, Hiroshima, Hiroshima, Japan*
[25] *National Institute of Radiological Science, Chiba, Chiba, Japan*
[26] *Ehime University, Matsuyama, Ehime, Japan*

TA detector

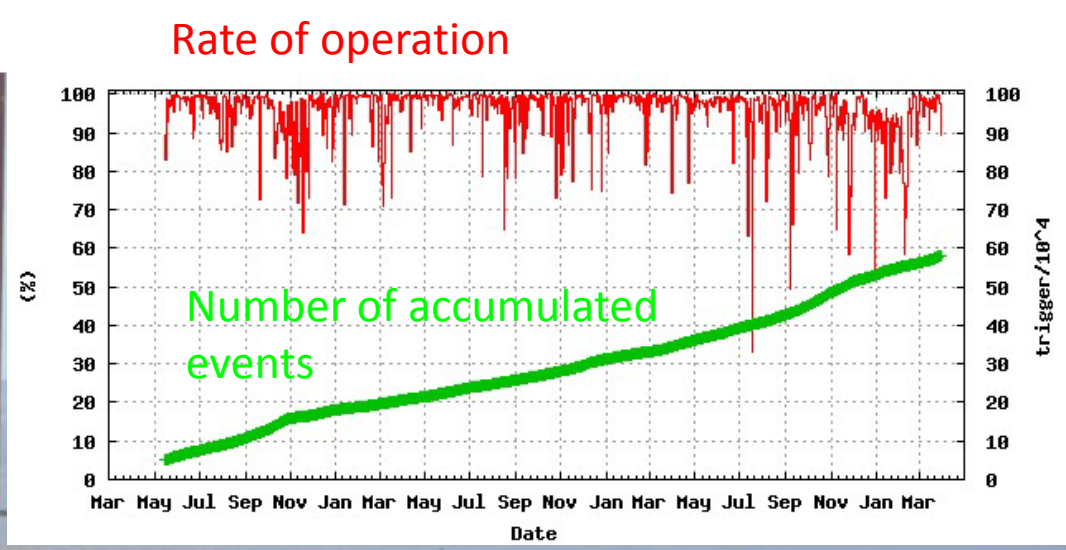
- **Surface detector (SD)**
  - Plastic scintillator (a la AGASA)
  - 507 SDs
  - 1.2km spacing, 680km^2
- **Fluorescence detector (FD)**
  - 3 stations（BR, LR, MD）
    - 38 telescopes（12＋12＋14）(a la HiRes)
- Location
  - Utah, USA
    - About 200km south to Salt Lake City
    - 39.3^{o}N, 112.9^{o}W
    - Altitude ~1400m

transfer HiRes telescopes



The largest detector in northern hemisphere

Surface Detector



Radio communication

Powered by solar cells

1.2 km spacing

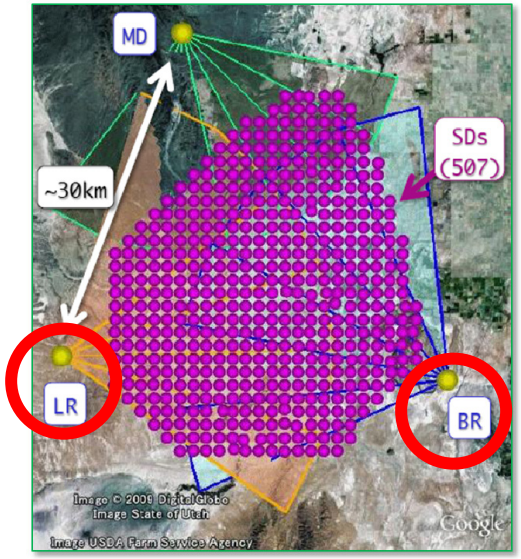
Plastic scintillator

- 3m^2, 1.2cm thickness
- 2 layers overlaid
- WLSF readout
- 50 MHz 12-bit FADC

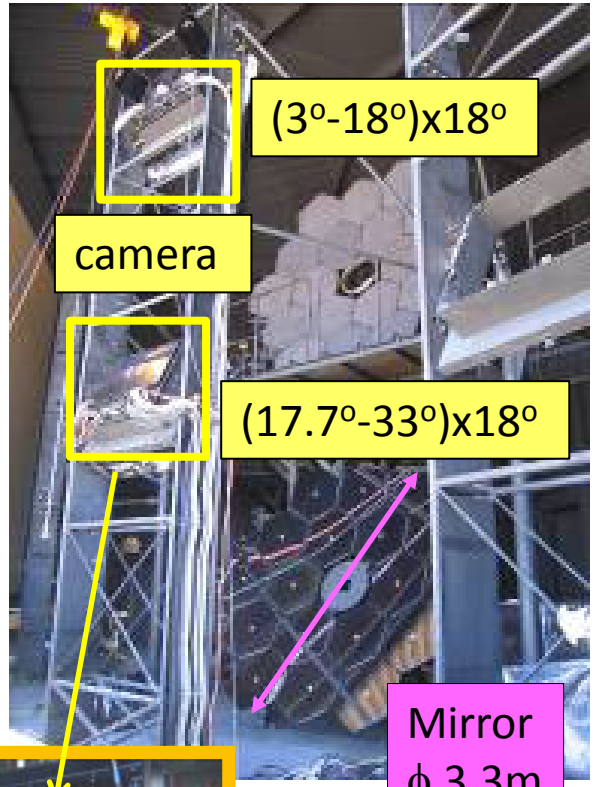
Operating as an SD array since March 2008

Fluorescence detector

- BR/LR site : new telescopes

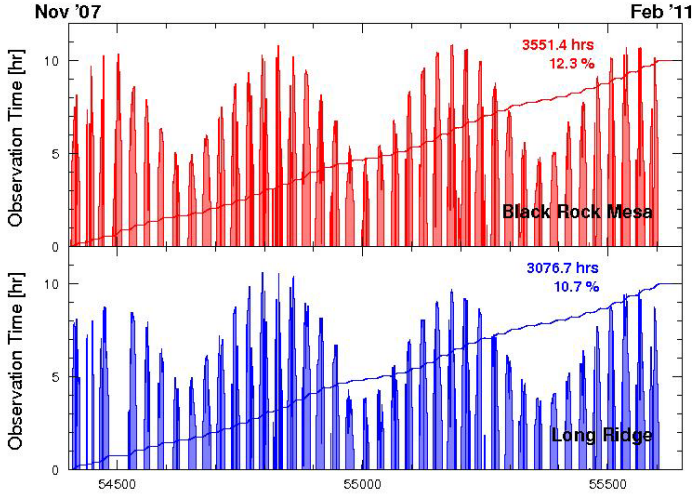


FOV: 3-33° in elevation
108° in azimuth

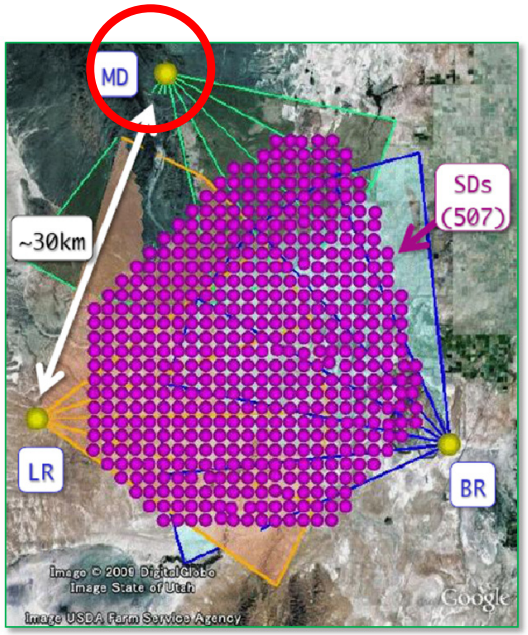


~1m

Camera
16x16=256 PMTs
Hamamatsu R9508



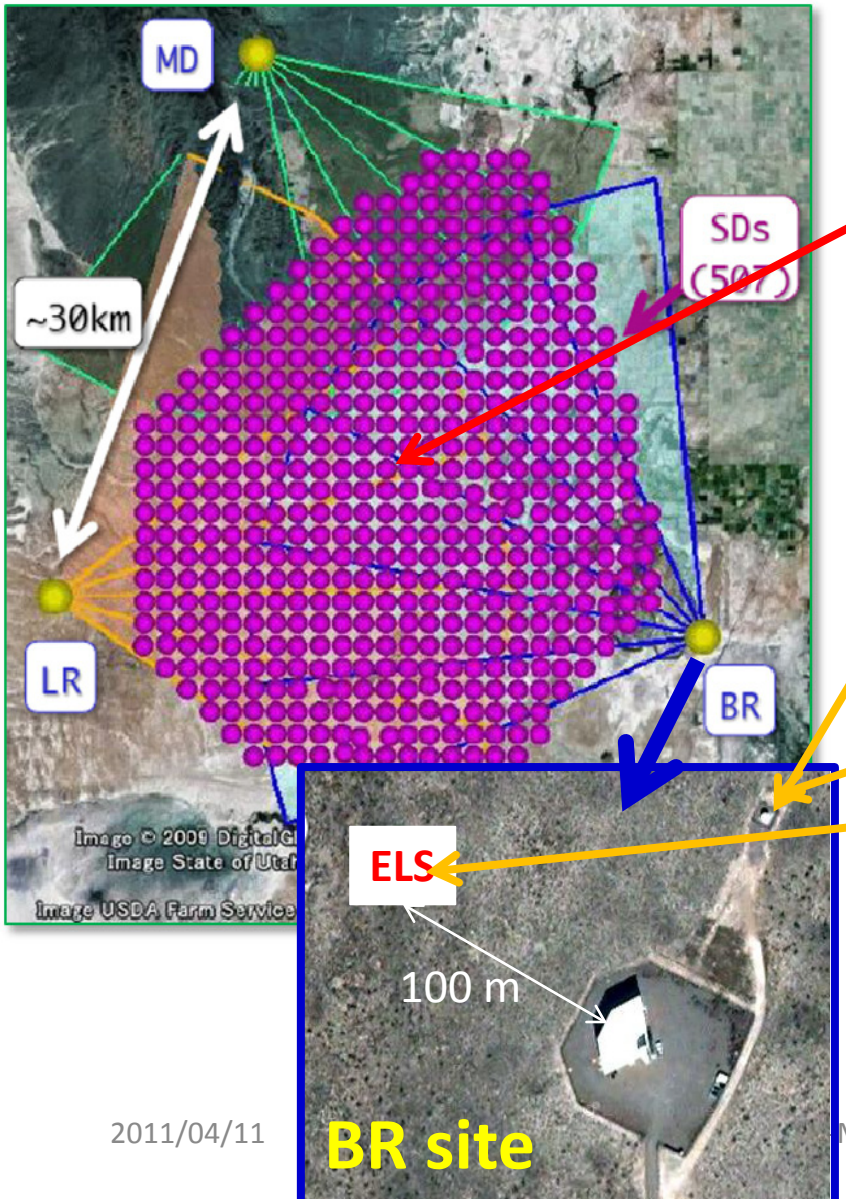
FD station at MD site



One FD station in the north
- 3^o-34^o evelvation with 1^o pixel

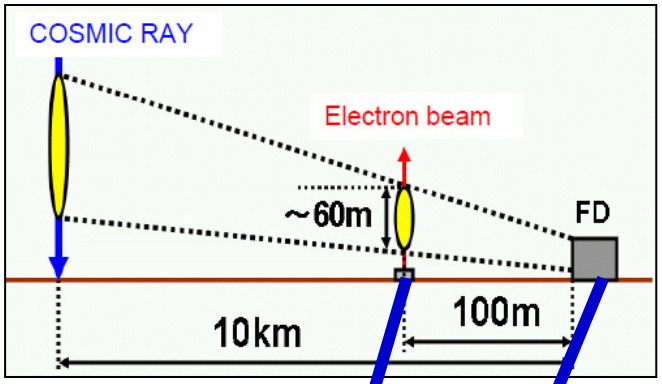
Transferred from HiRes
- $5.2m^2$ mirror
- S/H electronics

Atmospheric monitor・calibration
(for fluorescence detectors)



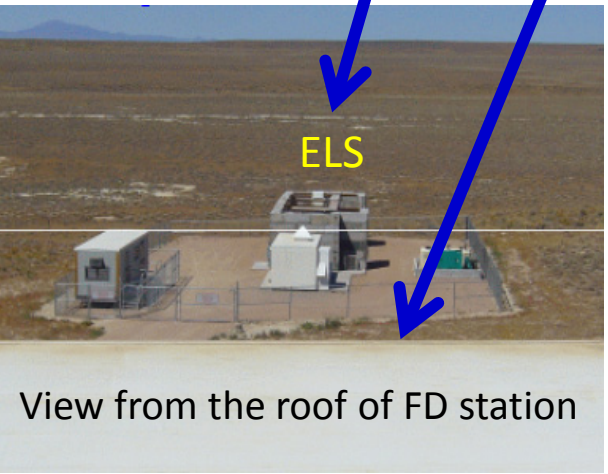
- Central Laser Facility
  - Observe sidescattering of laser from each FD station as a standard candle
- LIDAR :
  - Observe backscattering of laser→measure transparency of atmosphere
- IR camera : cloud monitor
- Electron Light Source (ELS)
  - Absolute energy calibration of fluorescence detectors

ELS (Electron Light Source)
[compact electron linear accelerator]

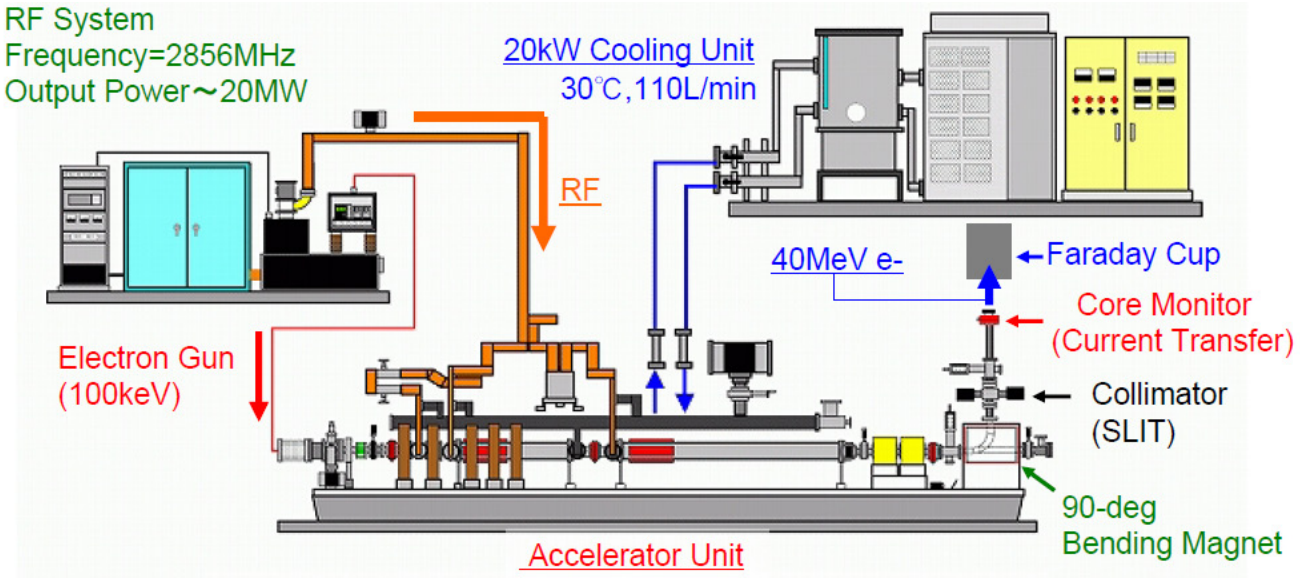


Specification

. electron energy: 40 MeV (max)
. current: 10^9 electrons/pulse
. pulse width: 1 μsec



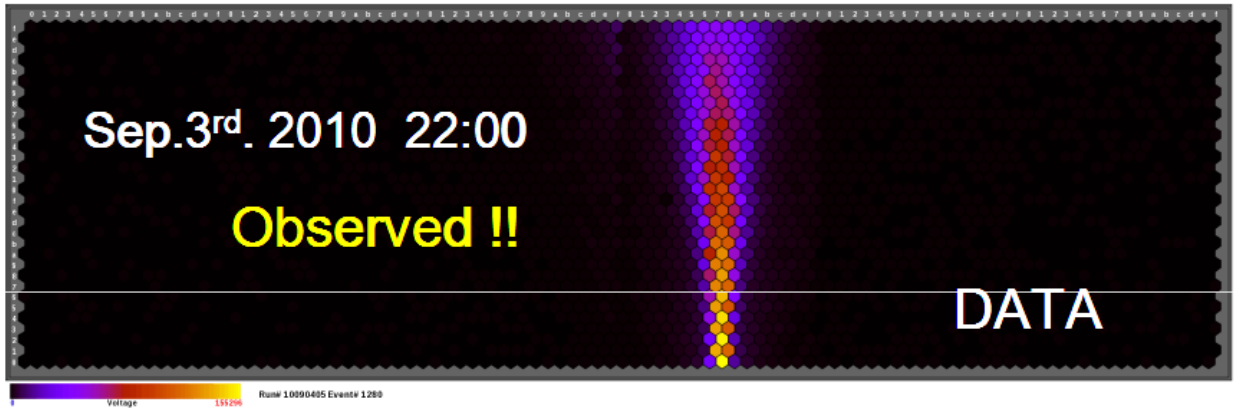
View from the roof of FD station

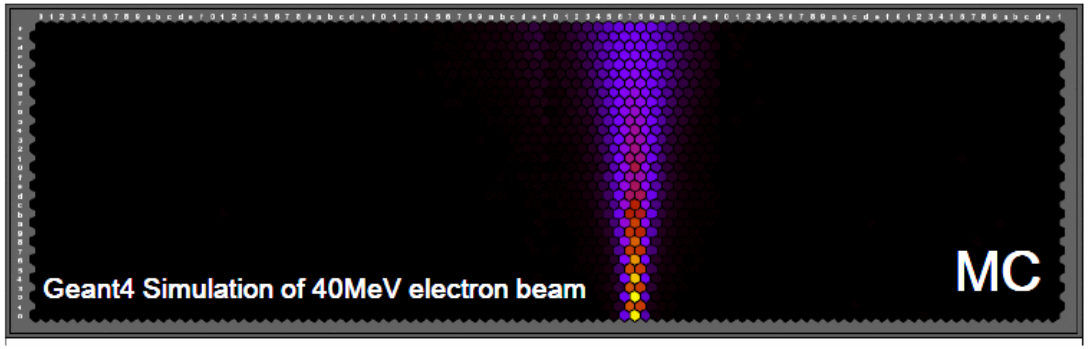


First light from ELS

FD Observation

Sep.3rd.2010 Beam Shot into the Sky, and Observed by FD





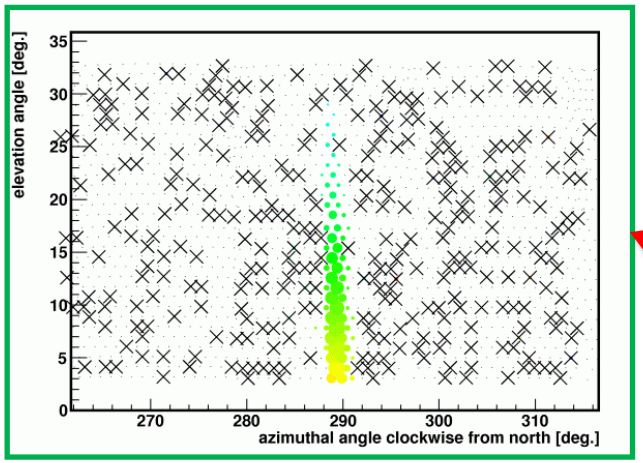
Spectrum

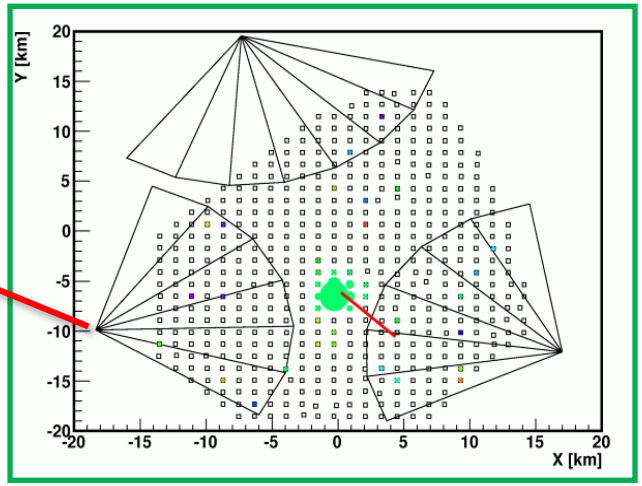
- Hybrid spectrum
  - BRM/LR FD (new telescopes) + SD
- MD FD mono spectrum
  - HiRes refurbished telescope
  - Direct comparison of energy scales and energy spectra between HiRes and TA
- SD spectrum
  - Plastic scintillator surface detectors (a la AGASA)

Hybrid Spectrum

- Hybrid analysis
  - FD mono analysis + SD information→improve reconstruction
  - Aperture is flat for >10^{19}eV by SD

The example of the Hybrid event
2008/12/30





Hybrid analysis: Data and MC

- **Geometry: Hybrid**
- **Energy: FD**

Data:

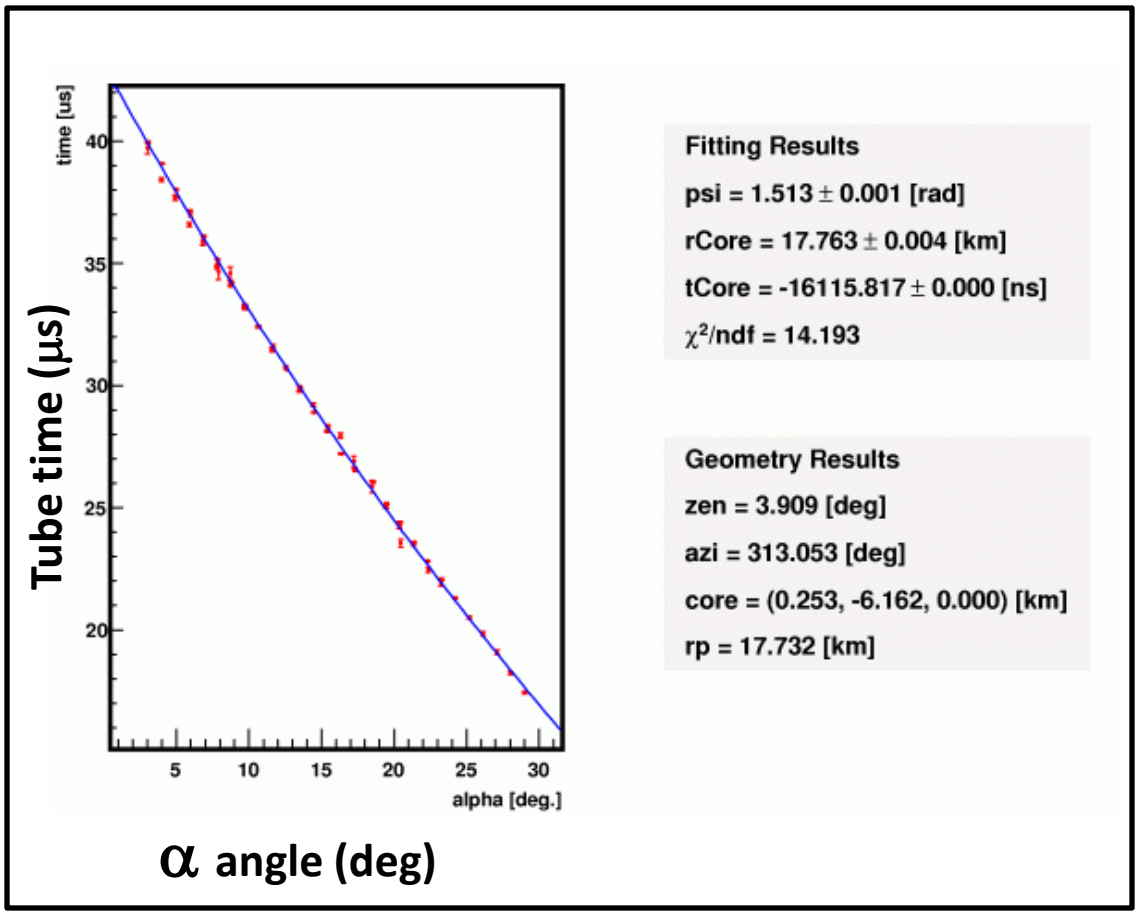
- date: May/27/2008 – Sep/28/2009 (~1.5years)
  - **BR + LR** (new telescopes) with SDs
  - 1978 events (FD-SD timing coincidence <200us)
- Cut condition
  - Xmax has to be observed.
  - Zenith angle < 45degrees

MC:

- Air shower:
  - COSMOS, proton, QGSJET-II
  - Slope: -3.1
  - Isotropic distribution
- Detector :
  - All of calibration constant with time dependence
  - Simulate trigger, front-end electronics, and DAQ
- Aperture / Exposure

Geometrical reconstruction

FD mono analysis + timing of one SD



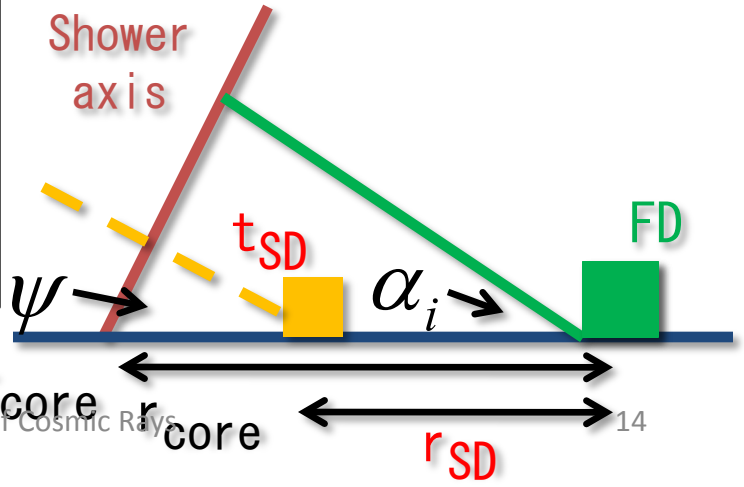
Mono reconstruction

$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

Hybrid reconstruction

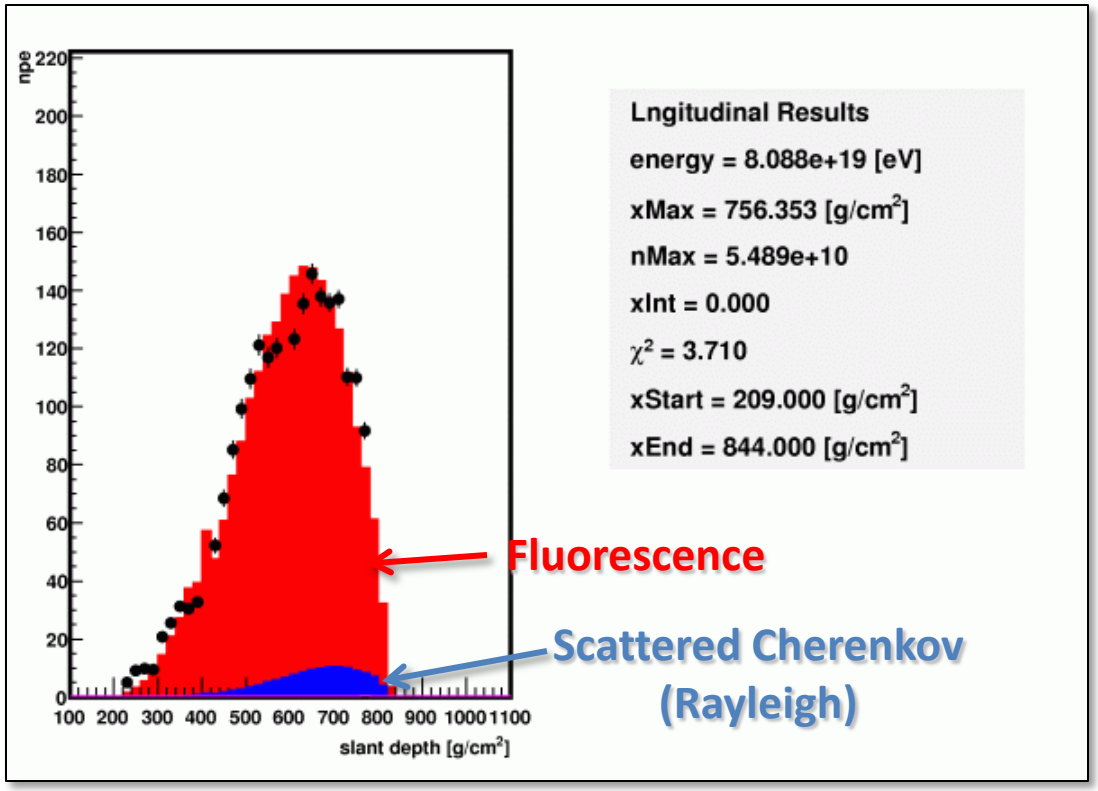
$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

$$t_{core} = t_{SD} + \frac{1}{c}(r_{core} - r_{SD})\cos\psi$$

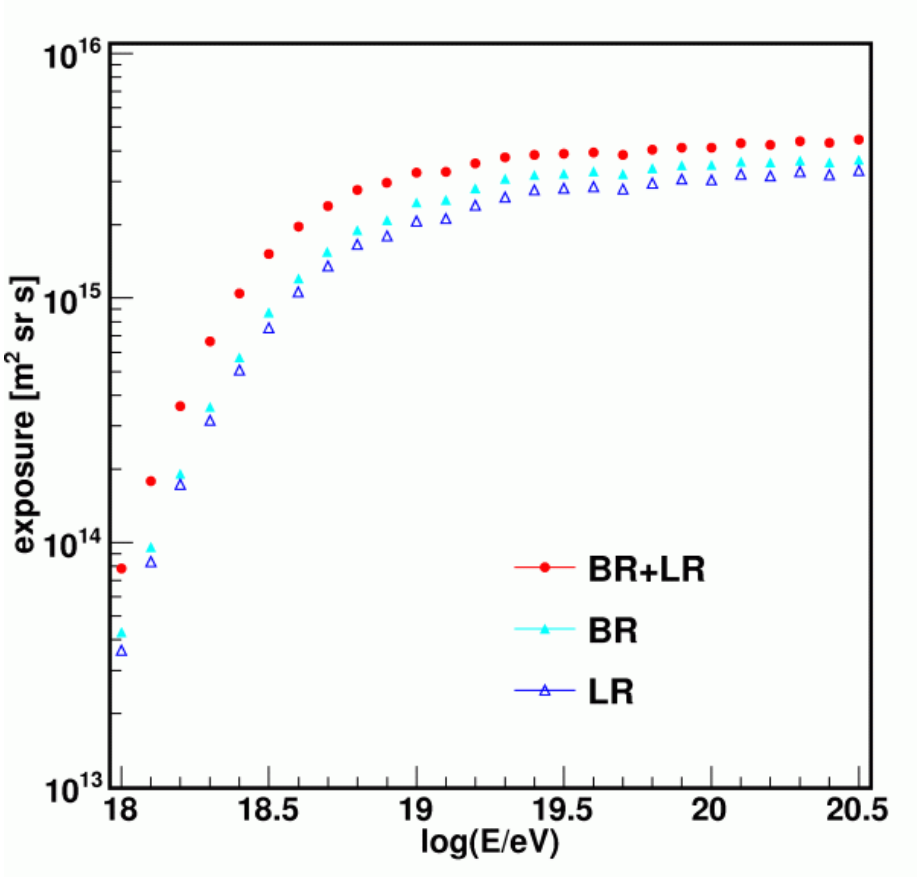


Shower profile reconstruction

- Xmax has to be observed
- Energy > $10^{18.65}$eV
- Zenith angle < 45 degree



Exposure



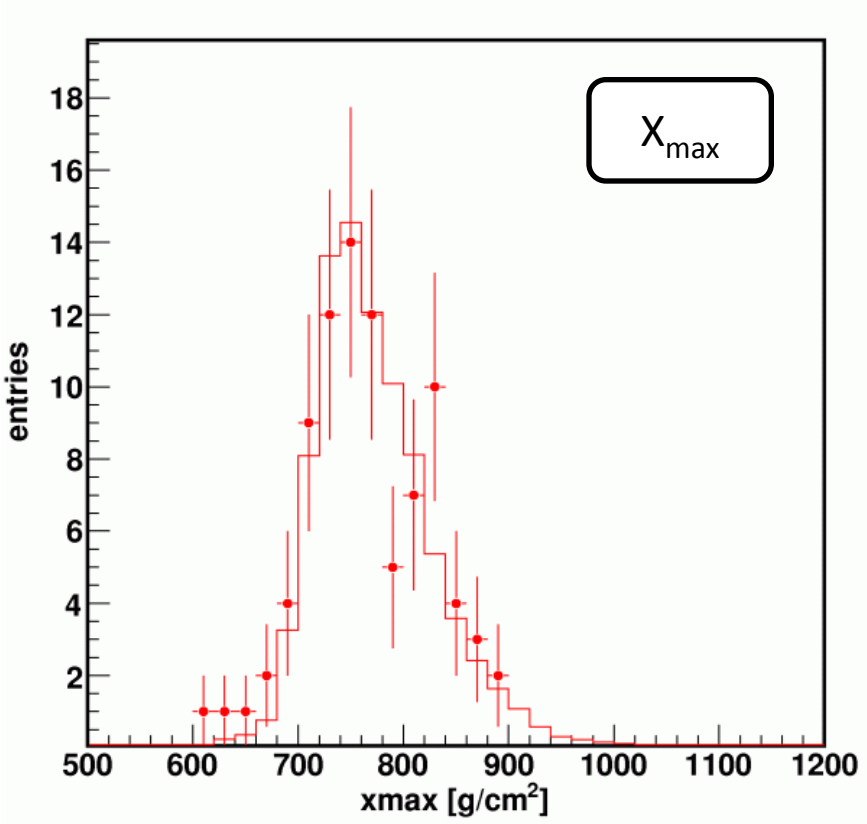
The aperture is calculated from MC simulation.

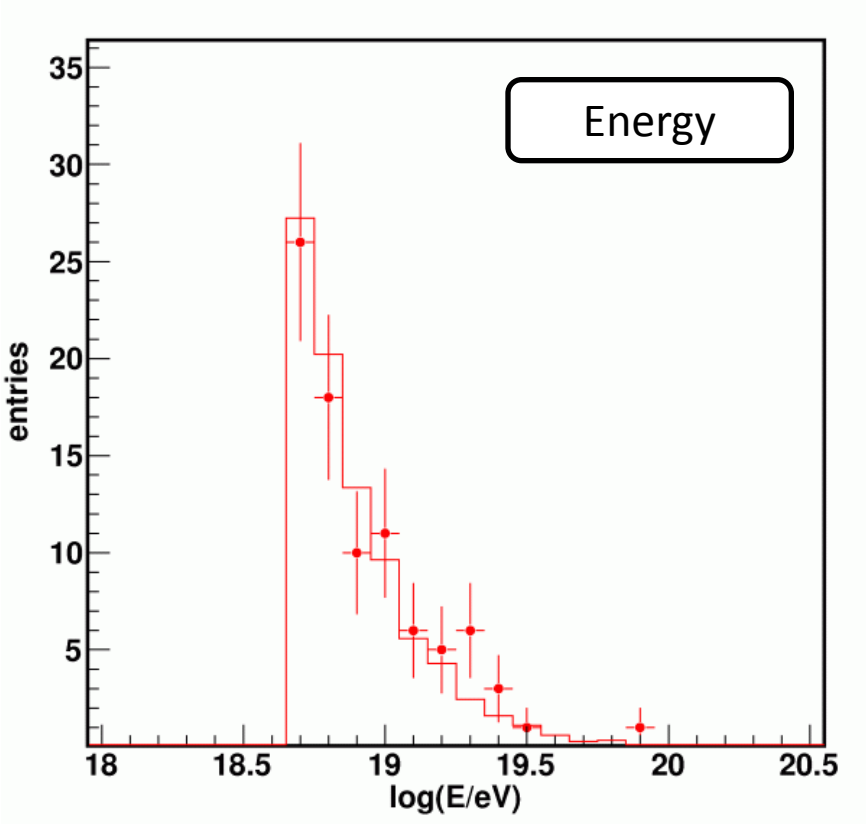
Exposure: ~3*10^{15} m^2 sr s (>~10^{19}eV)

(MC: Cosmos QGSJET II)

Data/MC comparison

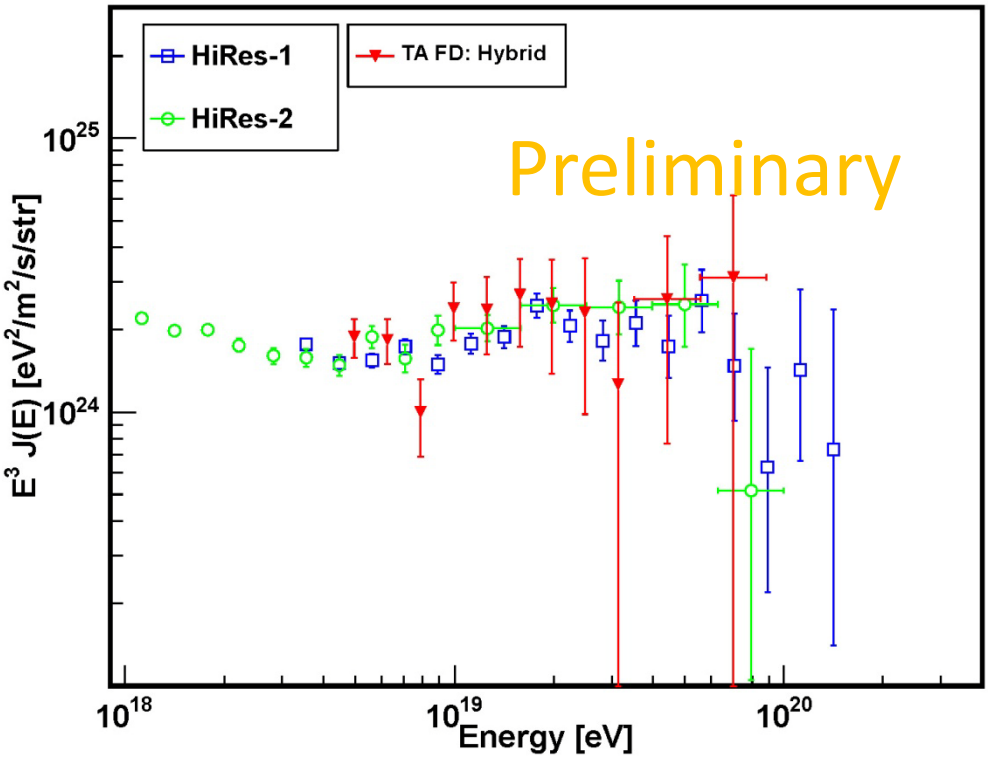
- BR station
- Filled circles : data
- Histograms : MC





Energy spectrum

- Hybrid events at the BR and LR station for TA 1.5 years



Systematic errors

Item	Systematic error
Fluorescence yield	12%
Detector	10%
Atmosphere	11%
Primary particle mass	5%
MC correction	3%
Total	19%

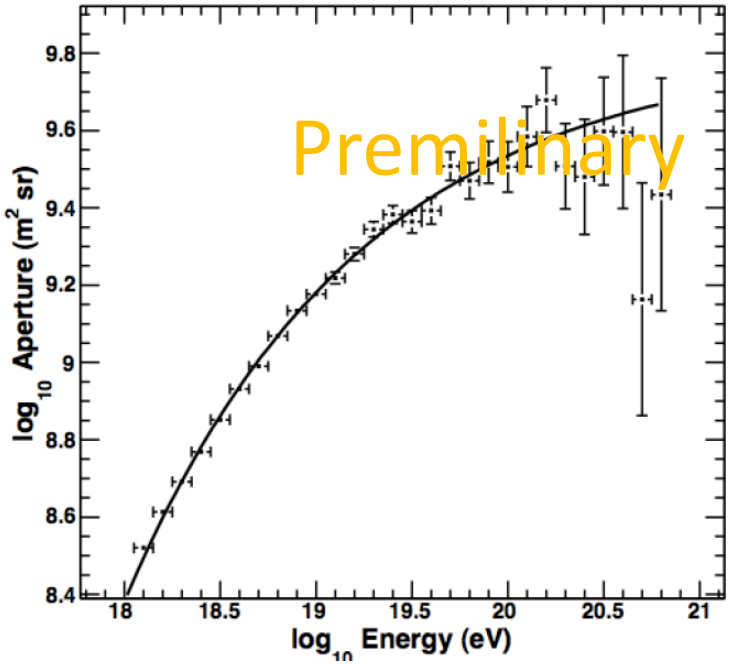
Middle Drum (MD) FD Analysis

- 14 refurbish HiRes-1 telescopes
- TAMD mono processing is identical to HiRes-1 monocular one.
  - Same program set, event selection, cuts
  - Using the same “average” atmospheric model
- The differences
  - the telescope location and pointing directions
  - Thresholds (~20% lower than HiRes-1)

MD mono energy spectrum

- Data: 2007/Dec~2010/Sep
- MC: CORSIKA/QGSJET events

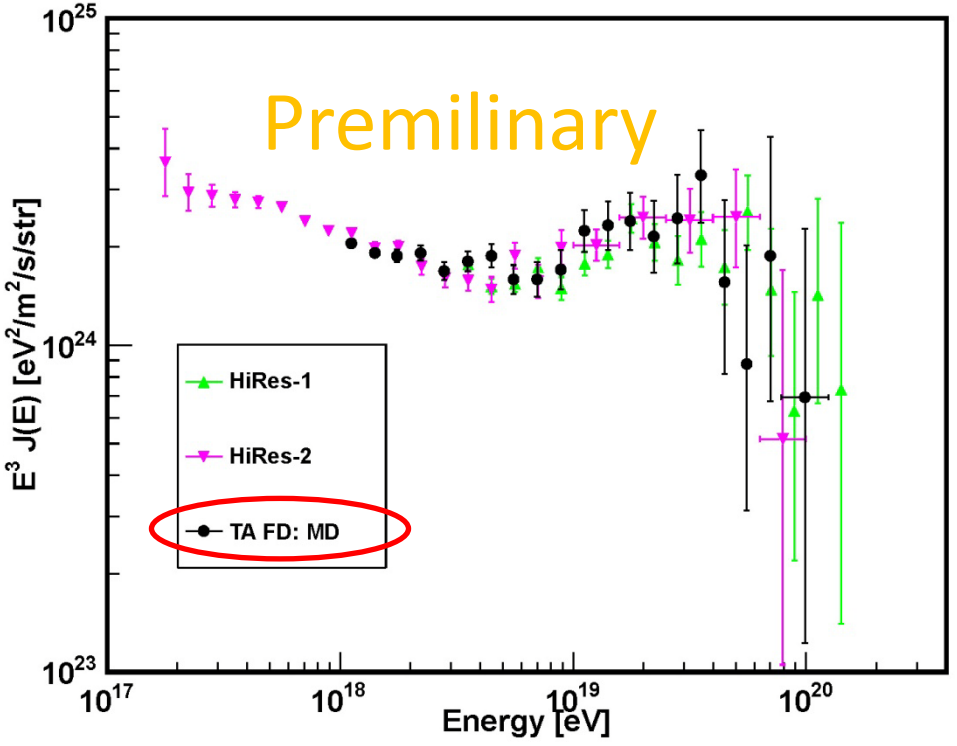
Aperture



~1/2 HiRes ($E>10^{19}$eV)

~1/4 the exposure of HiRes-1

Spectra



in good agreement with HiRes

SD spectrum

- SD reconstruction
  - LDF, timing fit
- MC
  - First energy estimation
- Data/MC comparisons
  - SD energy vs. FD energy
- SD spectrum

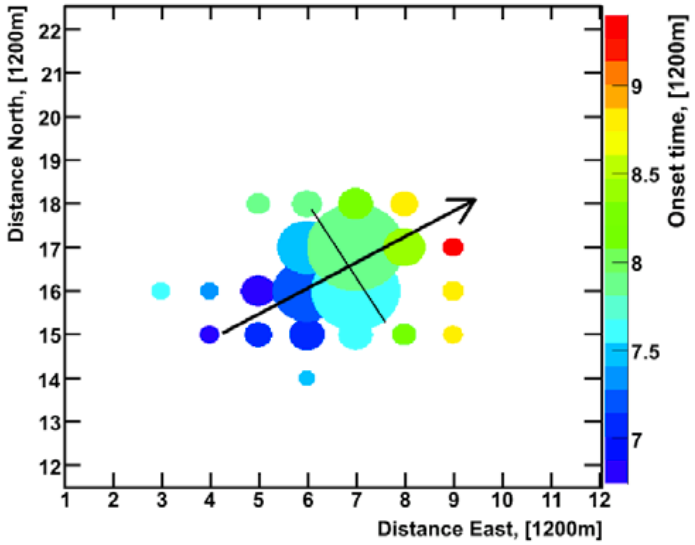
Data set

- May/2008 – Feb/2010 (1.75 years)
- Exposure ~1500km^2 sr yr (~AGASA 13 years)
- Cuts:
  - LDF χ^2/ndf < 4.0
  - Border Cut > 1.2km
  - Zenith Angle < 45 degrees
  - Pointing direction uncertainty < 5 degrees
  - Fractional S800 uncertainty < 0.25

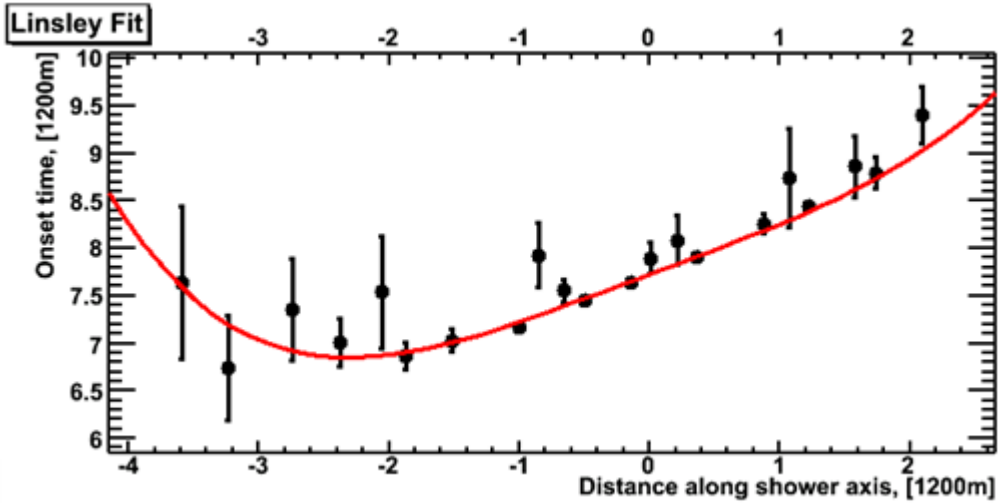
→ 6264 events

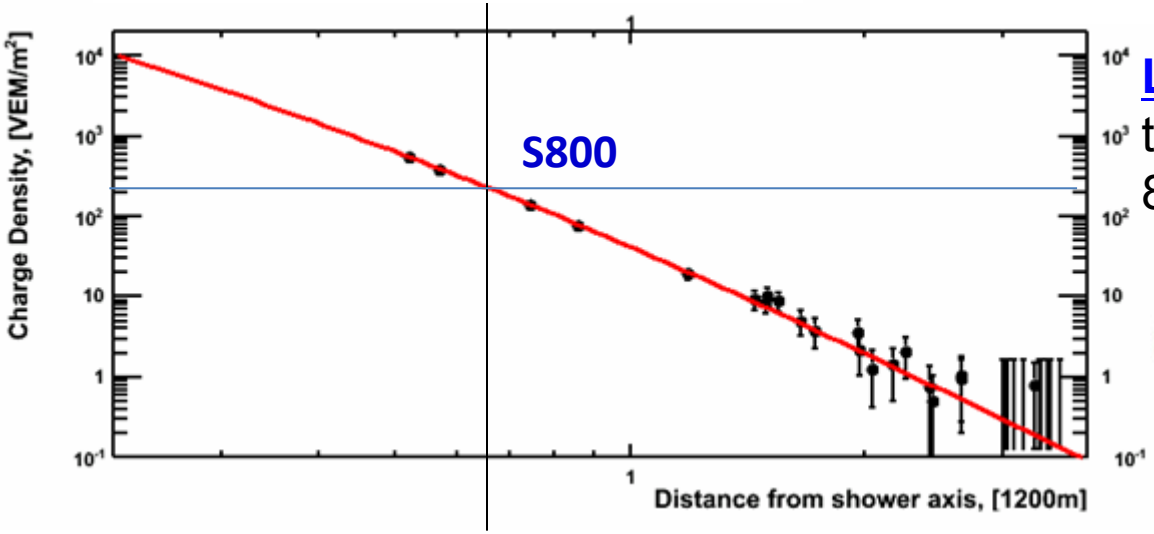
SD event reconstruction

2008/Jun/25 - 19:45:52.588670 UTC



Time fit to determine **geometry**
(modified Linsley)





r = 800m

Lateral Density Distribution Fit
to determine **S800** (charge density 800m from the shower axis)

Fit with AGASA LDF

$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2} \left(1+\frac{r}{R_M}\right)^{-(\eta-1.2)} \left\{1+\left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

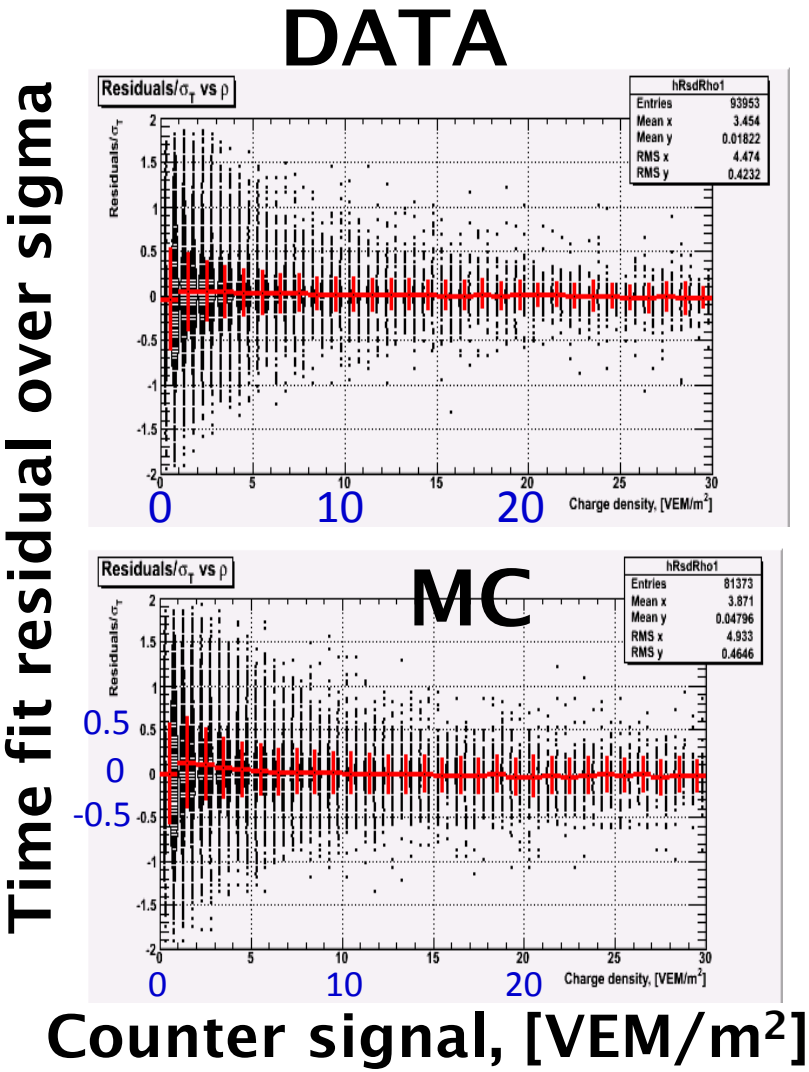
$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62)\,(\sec\theta - 1)$$

- S(800)→Primary Energy

SD Monte Carlo

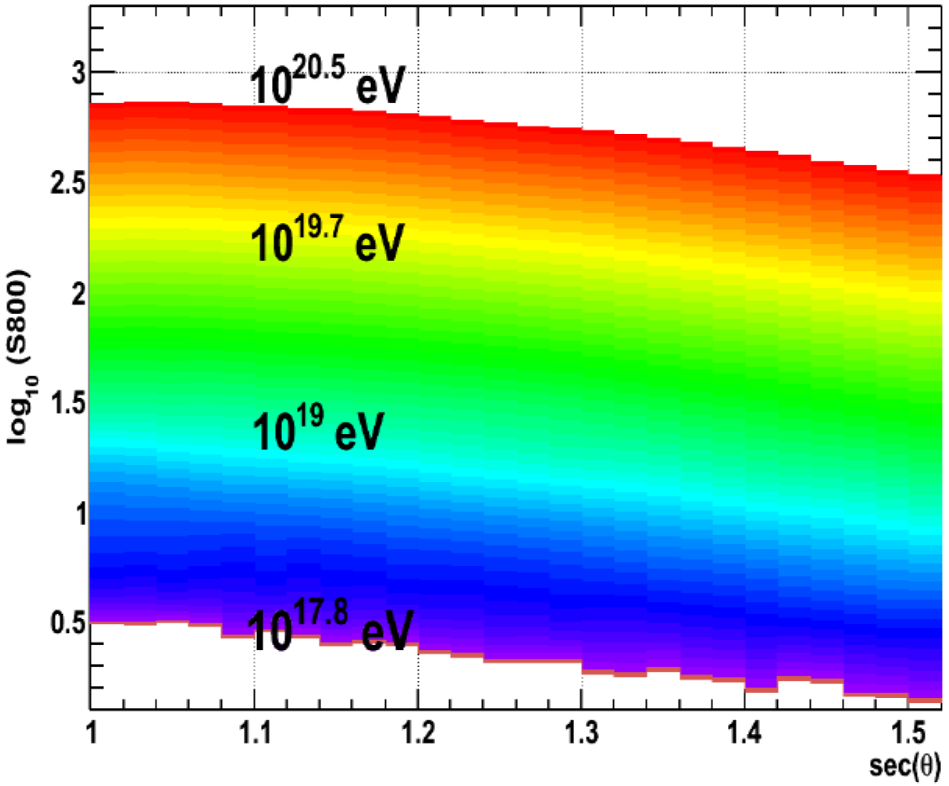
- Simulate the data exactly as it exists.
  - Start with previously measured spectrum and composition.
  - **Use Corsika/QGSJet-II air shower events.**
  - Throw with isotropic distribution.
  - Simulate detector response (GEANT4), trigger, front-end electronics, DAQ.
  - Write out the MC events in same format as data.
  - Analyze the MC with the same programs used for data.
- Test with data/MC comparison plots.

Fitting results



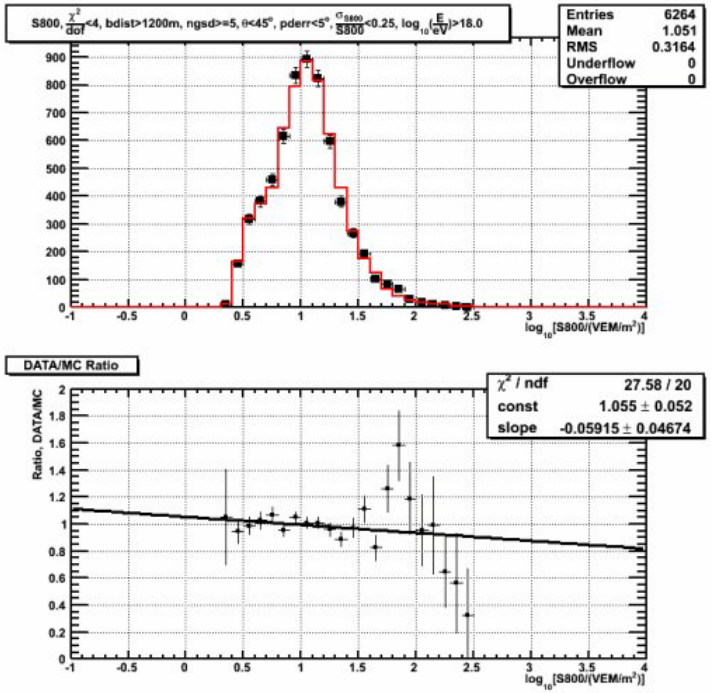
- Fitting procedures are derived solely from the data
- Same analysis is applied to MC
- Fit results are compared between data and MC
- MC fits the same way as the data.
- Consistency for both time fits and LDF fits.
- Corsika/QGSJet-II and data have same lateral distributions!

First Estimate of Energy

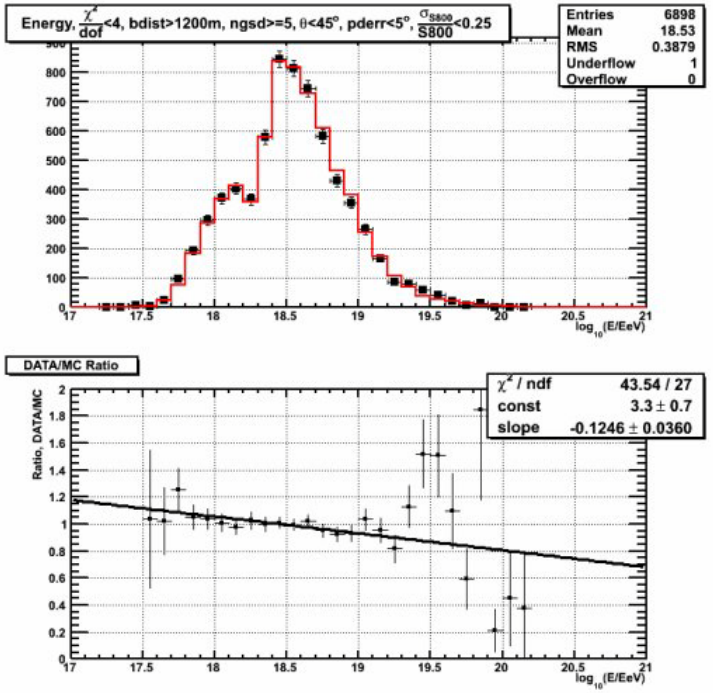


- Energy table is constructed from the MC
- First estimation of the event energy is done by interpolating between S800 vs sec(θ) lines

DATA/MC: S800, Energy

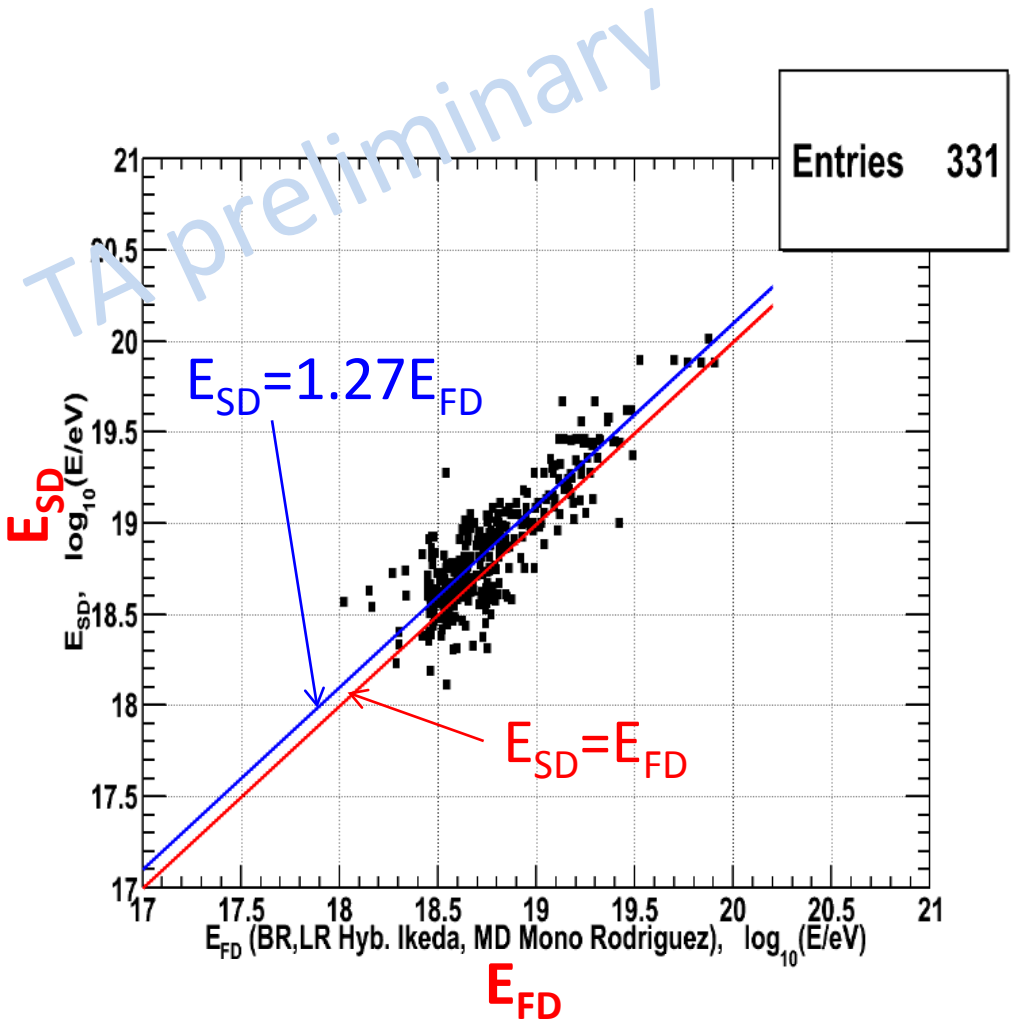


S800



Energy

Comparison of E_{SD} and E_{FD}

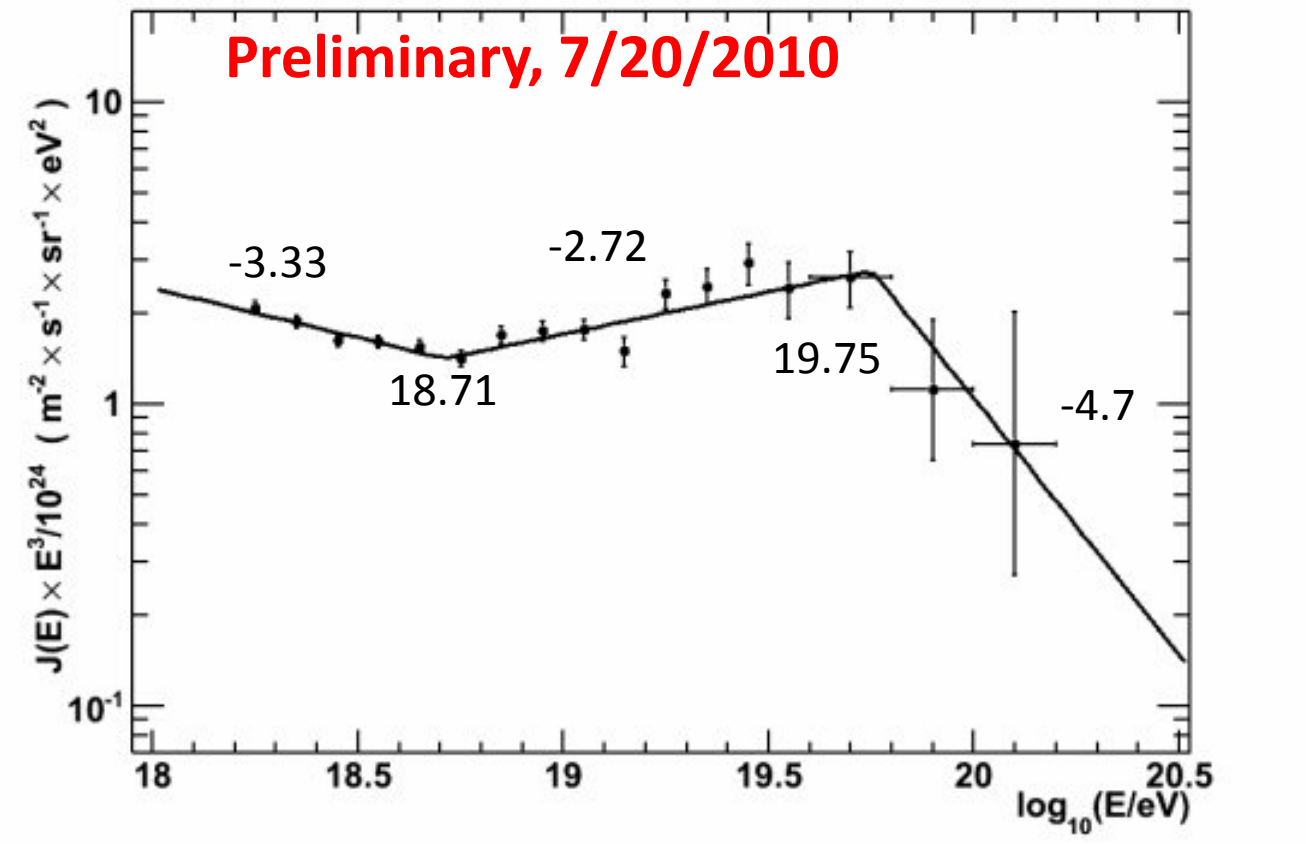


- Energy scale is determined experimentally by FD without referring to MC.
- Set SD energy scale to FD energy scale using well-reconstructed events detected by both detectors.
- 27% renormalization.
  - Systematic error 19%

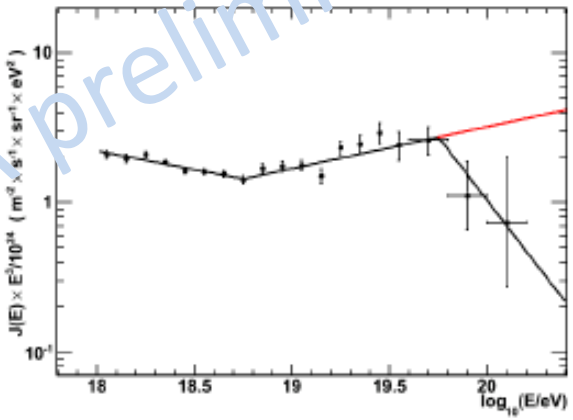
    (from systematic error of energy by hybrid analysis)

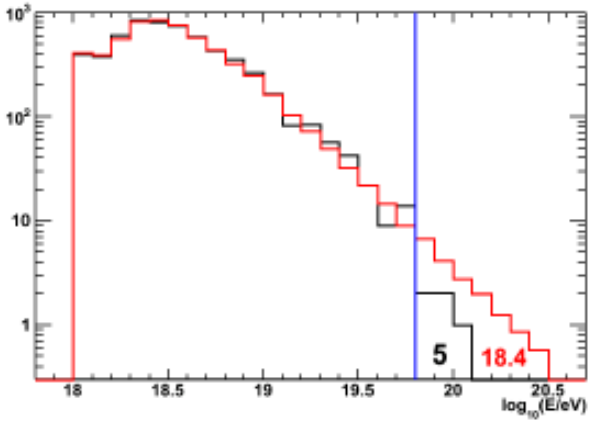
TA SD Spectrum

TA SD energy is rescaled to FD energy.



Significance of the Suppression





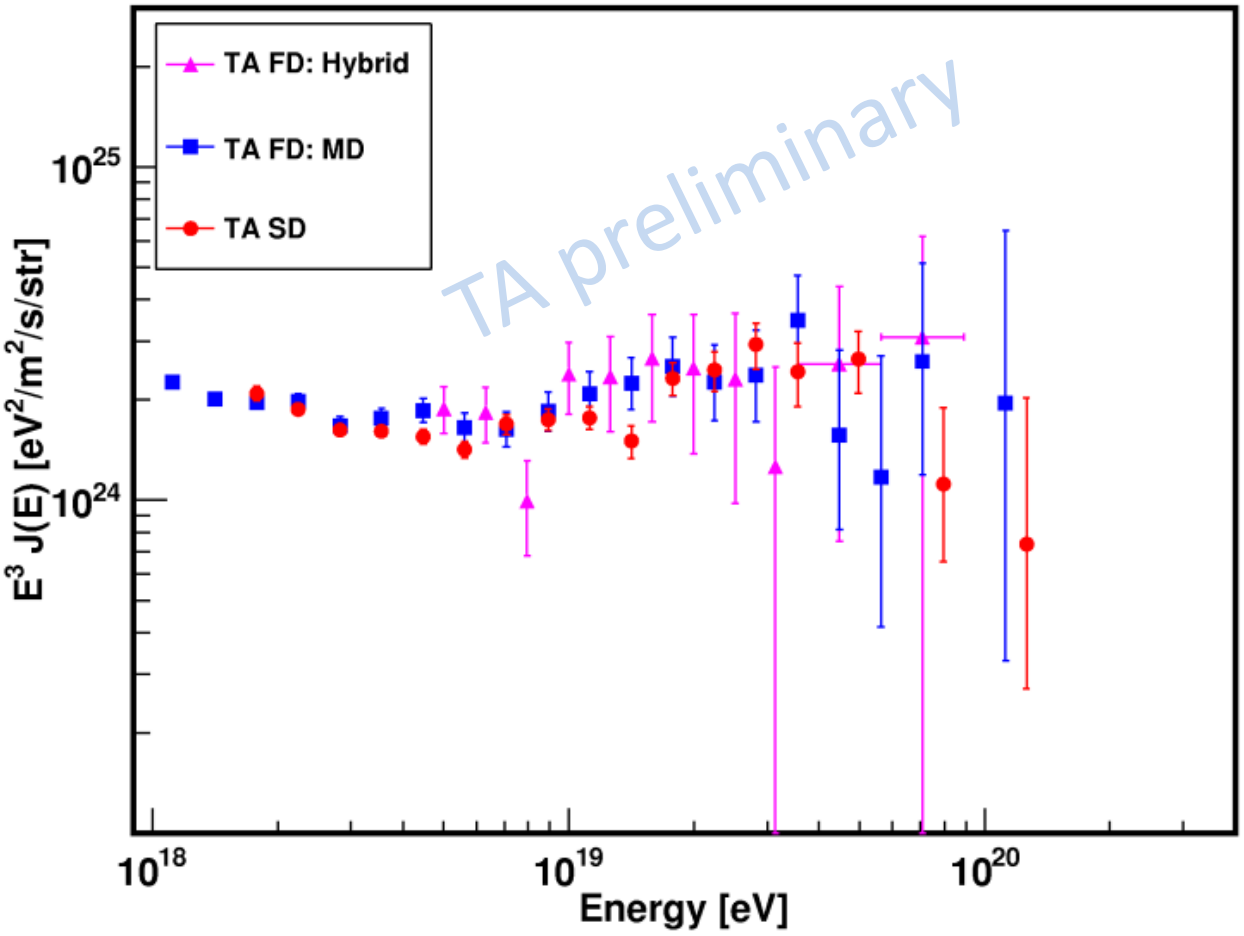
- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TASD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}$E bins after $10^{19.8}$eV bin:
  - $N_{EXPECT} = 18.4$
  - $N_{OBSERVE} = 5$

$$\text{PROB} = \sum_{i=0}^{5} Poisson(\mu = 18.4; i) = 2.41 \times 10^{-4}$$

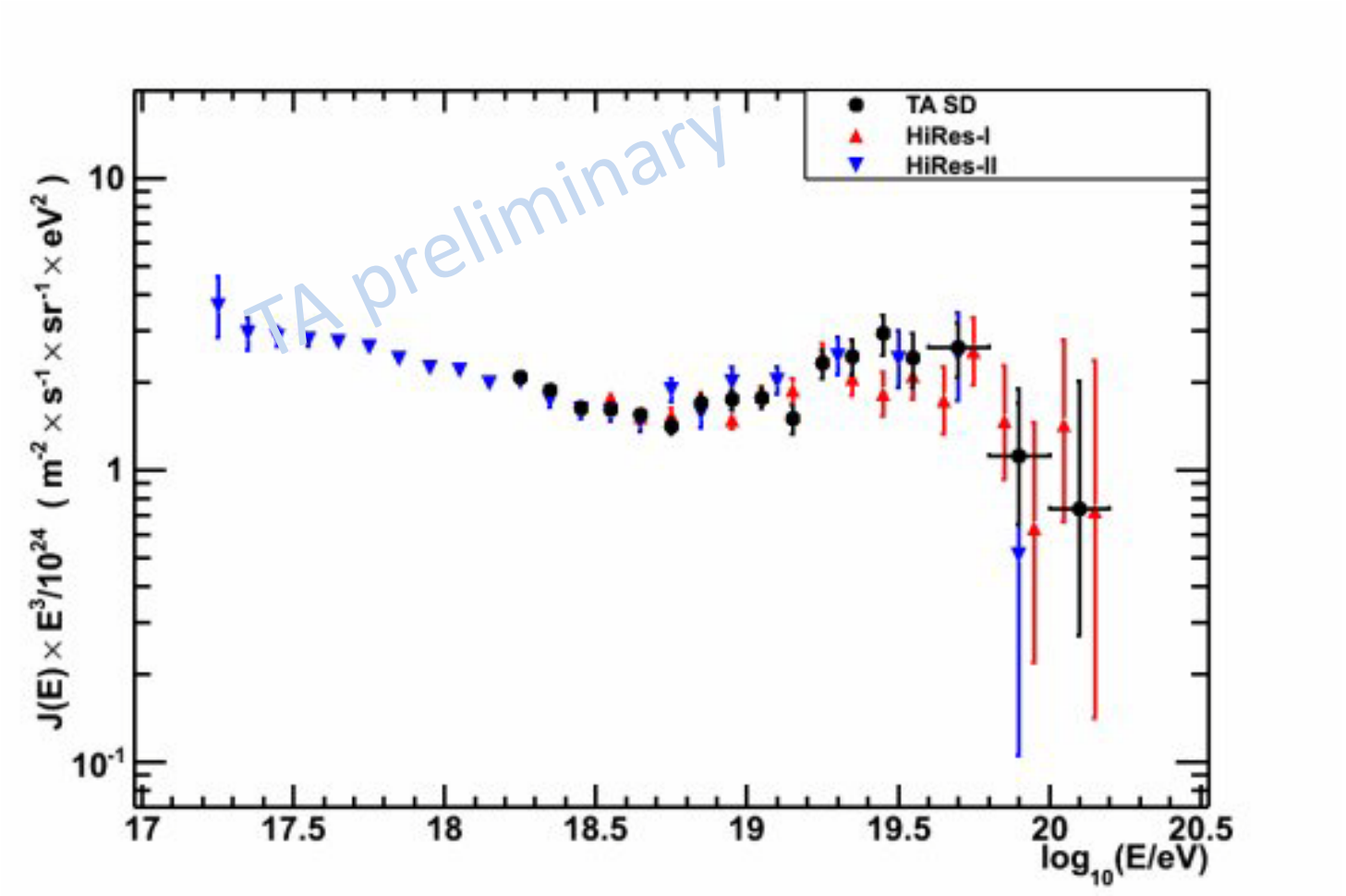
(3.5σ)

TA SD energy is rescaled to FD energy.

TA SD, Middle Drum FD Monocular, and TA Hybrid Spectra

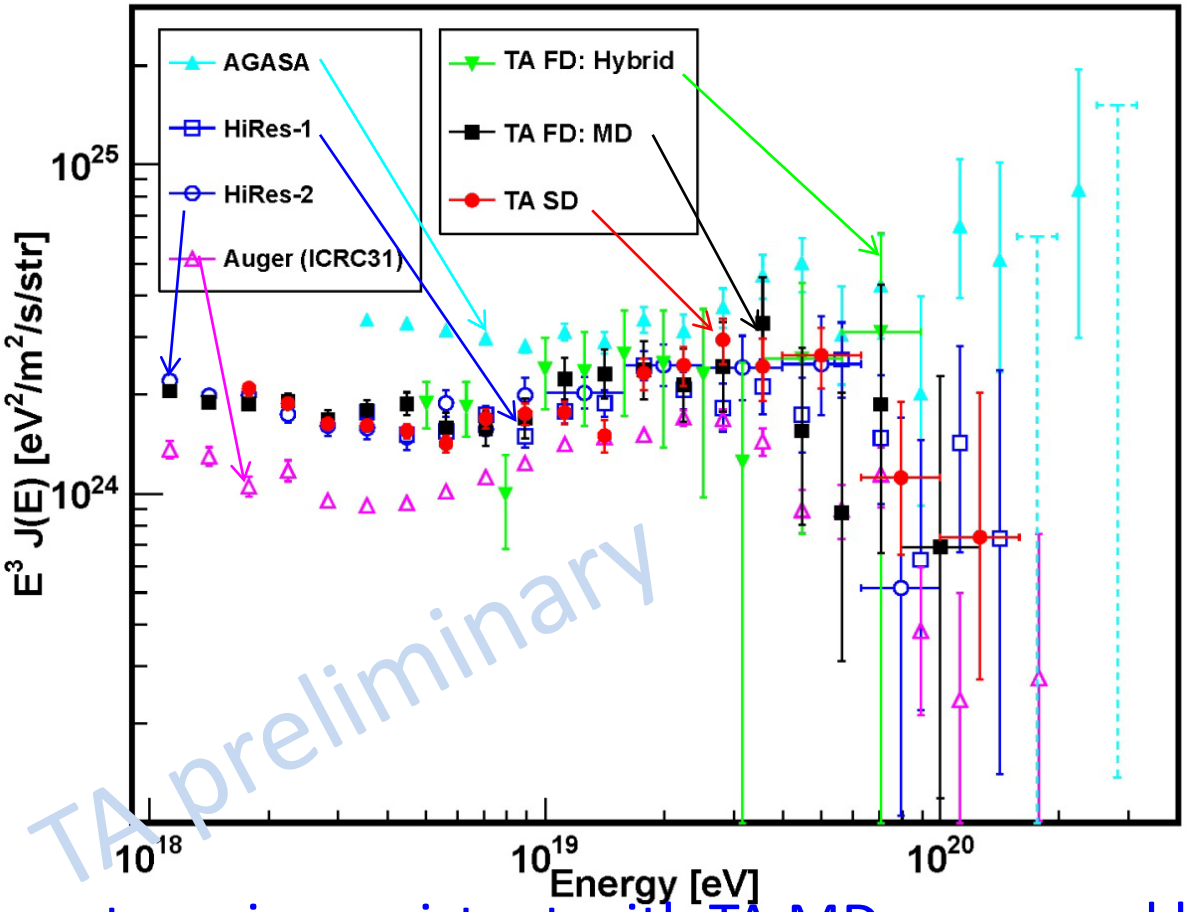


TA SD and HiRes Spectra



TA, AGASA, Auger, HiRes, AGASA spectra

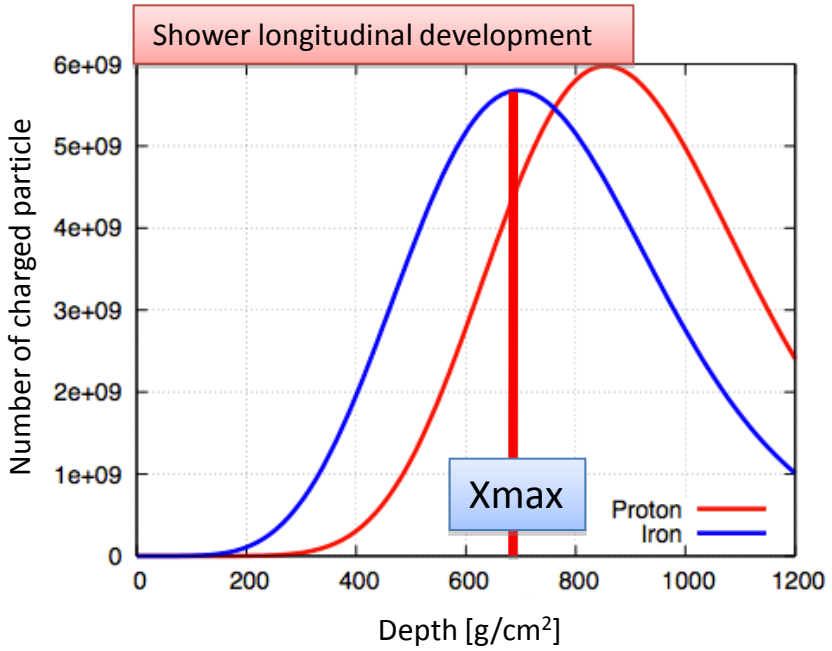
TA SD energy is scaled to FD energy.



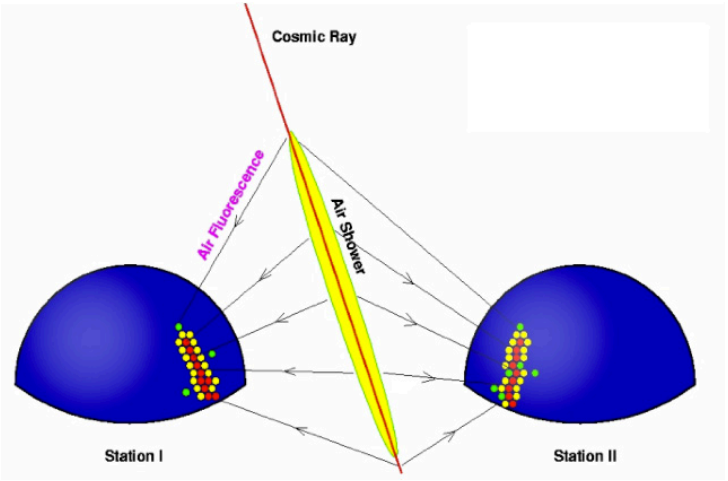
TA SD spectrum is consistent with TA MD mono and hybrid spectra, and consistent with HiRes-I and HiRes-II spectra.

Mass composition
(Xmax technique)

- Shower longitudinal development strongly depends on their primary particle type.
- FD observes shower development directly.
- Xmas is one of the efficient parameter for determining primary particle type.

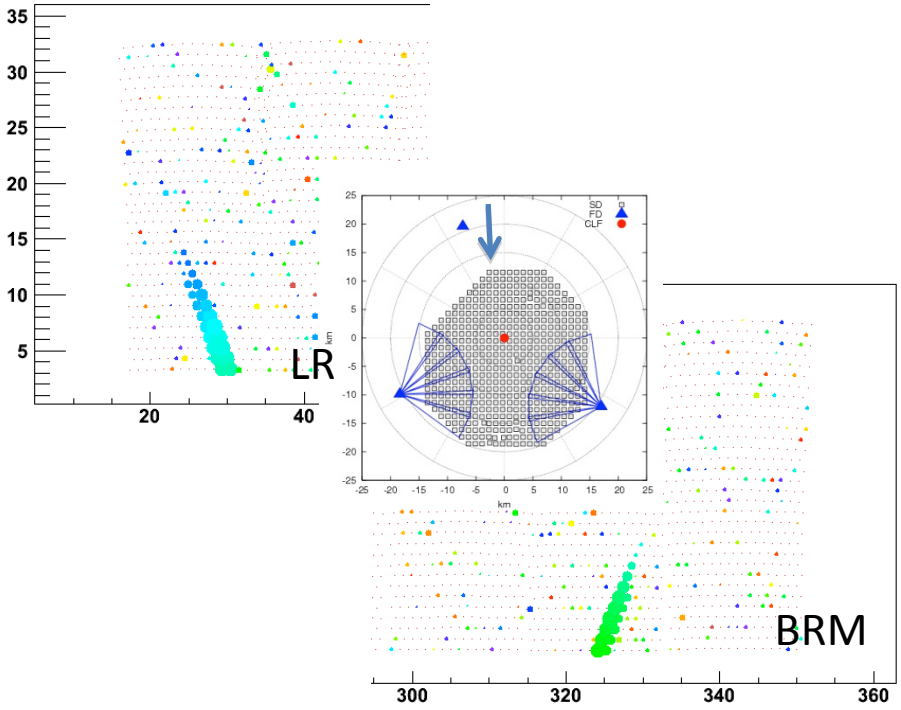


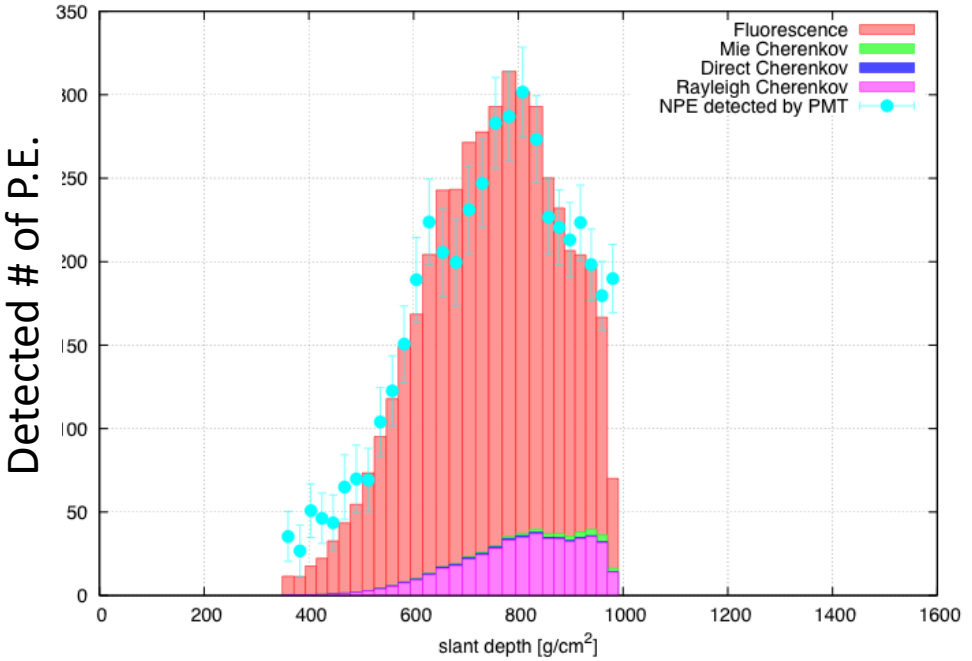
FD stereo analysis



Shower axis is determined better by FD stereo reconstruction than by FD mono reconstruction.

FD Stereo Event



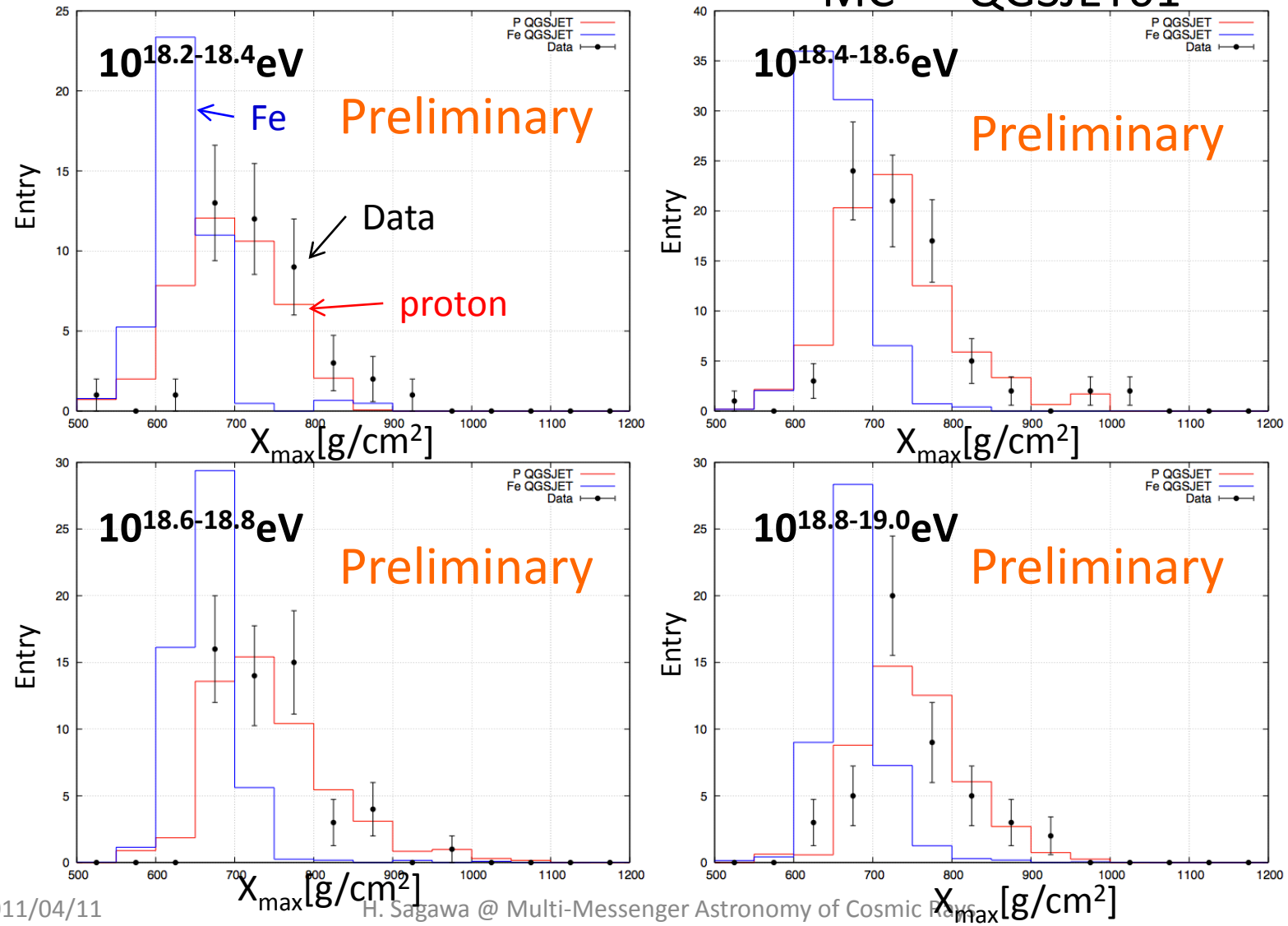


Date	log(E/eV)	Xmax	zenith	azimuth	Xcore	Ycore
2008/09/04	19.71	890 g/cm^2	44.3^o	-3.0^o	-3.1	14.2

X_{max} Data/MC comparison

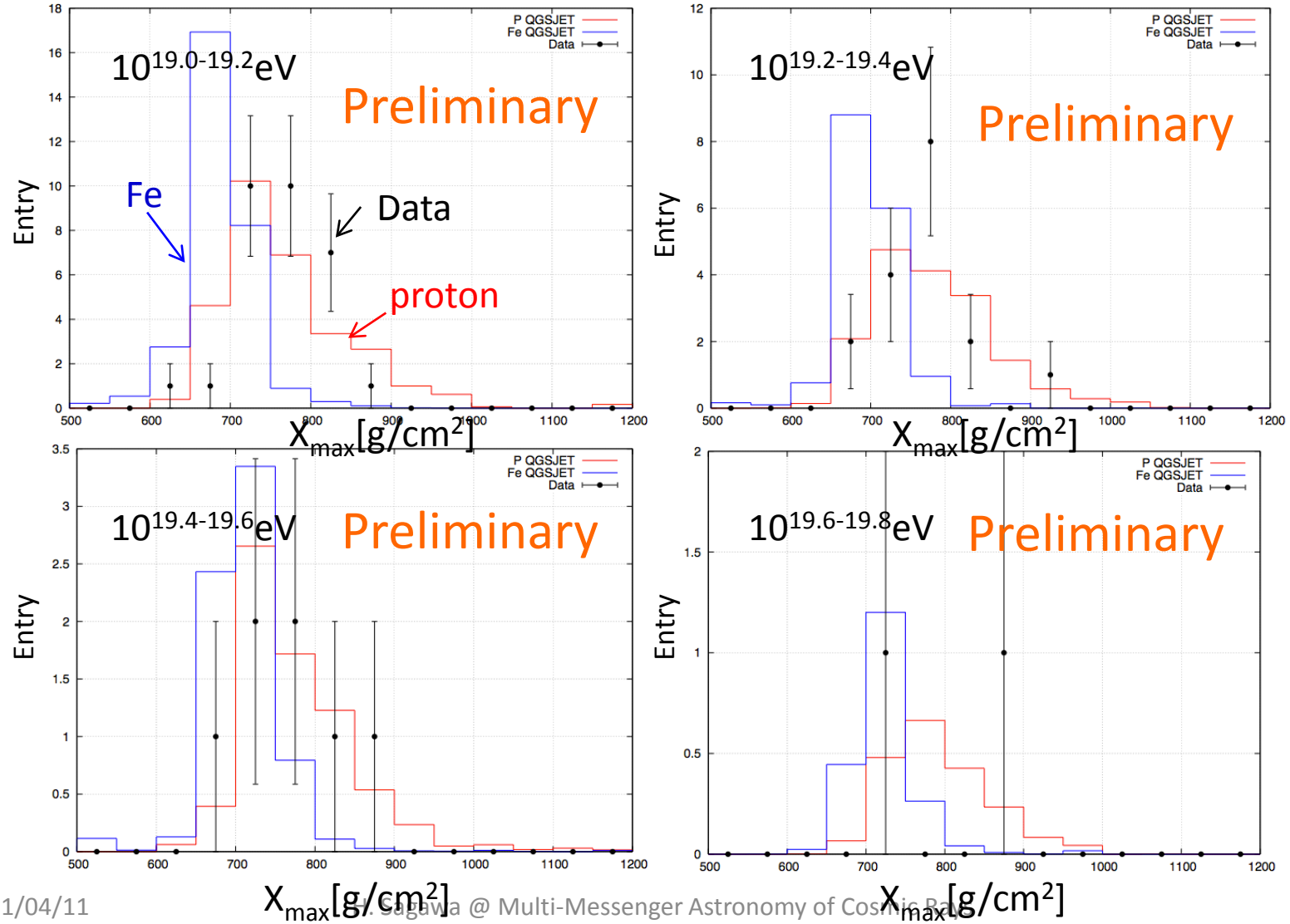
Dataset: 2007/Nov ~ 2010/Sep (~3yrs)

X_{max} = reconstructed X_{max}
MC = QGSJET01



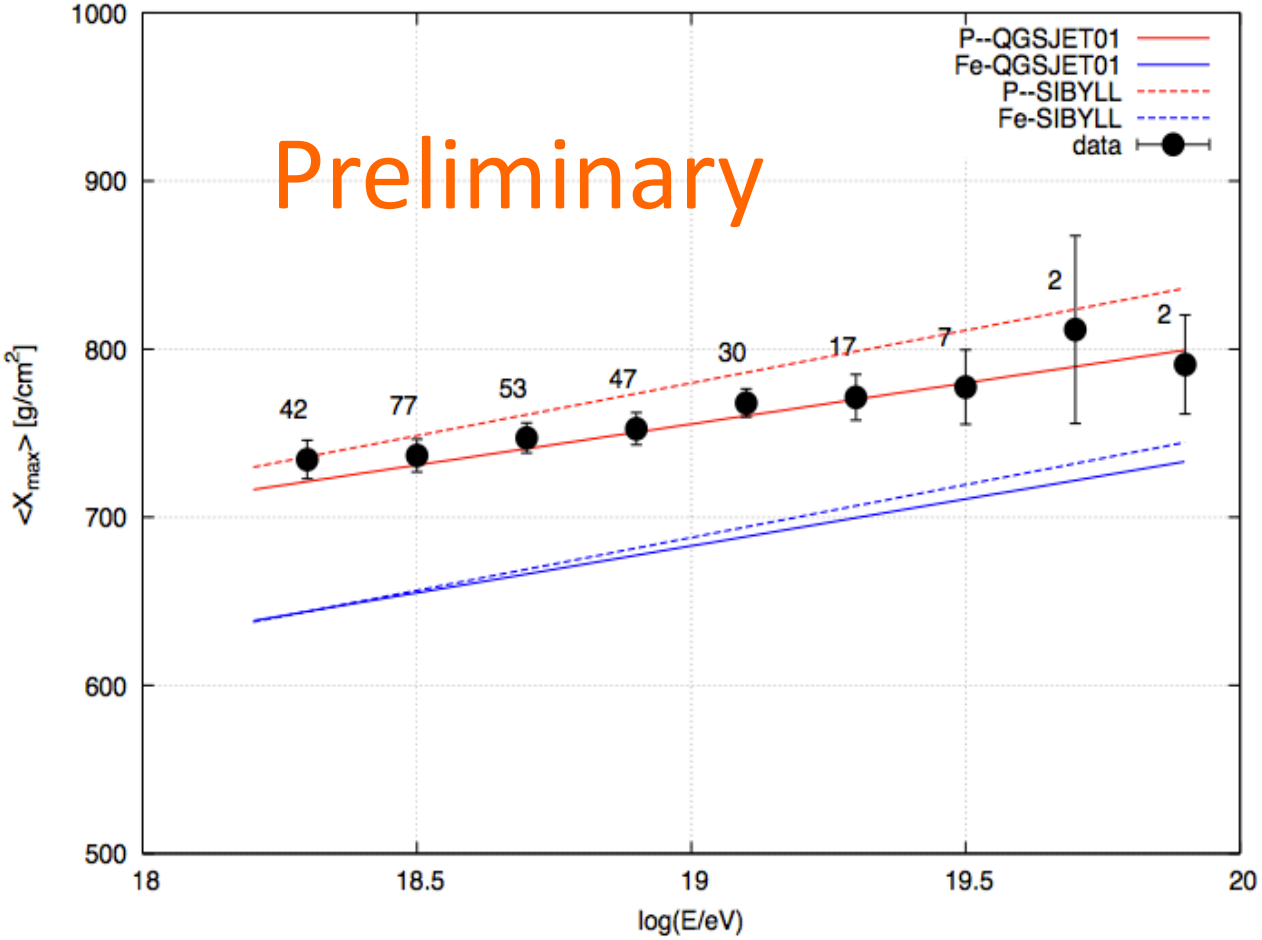
X_{max} Data/MC comparison

X_{max} = reconstructed X_{max}
MC = QGSJET01



$\langle X_{max} \rangle$ vs. Energy

X_{max}= reconstructed X_{max}
Energy=reconstructed energy



Mass composition of TA data is consistent with proton prediction.

Anisotropy

- LSS correlation
- AGN correlation
- autocorrelation

LSS correlation

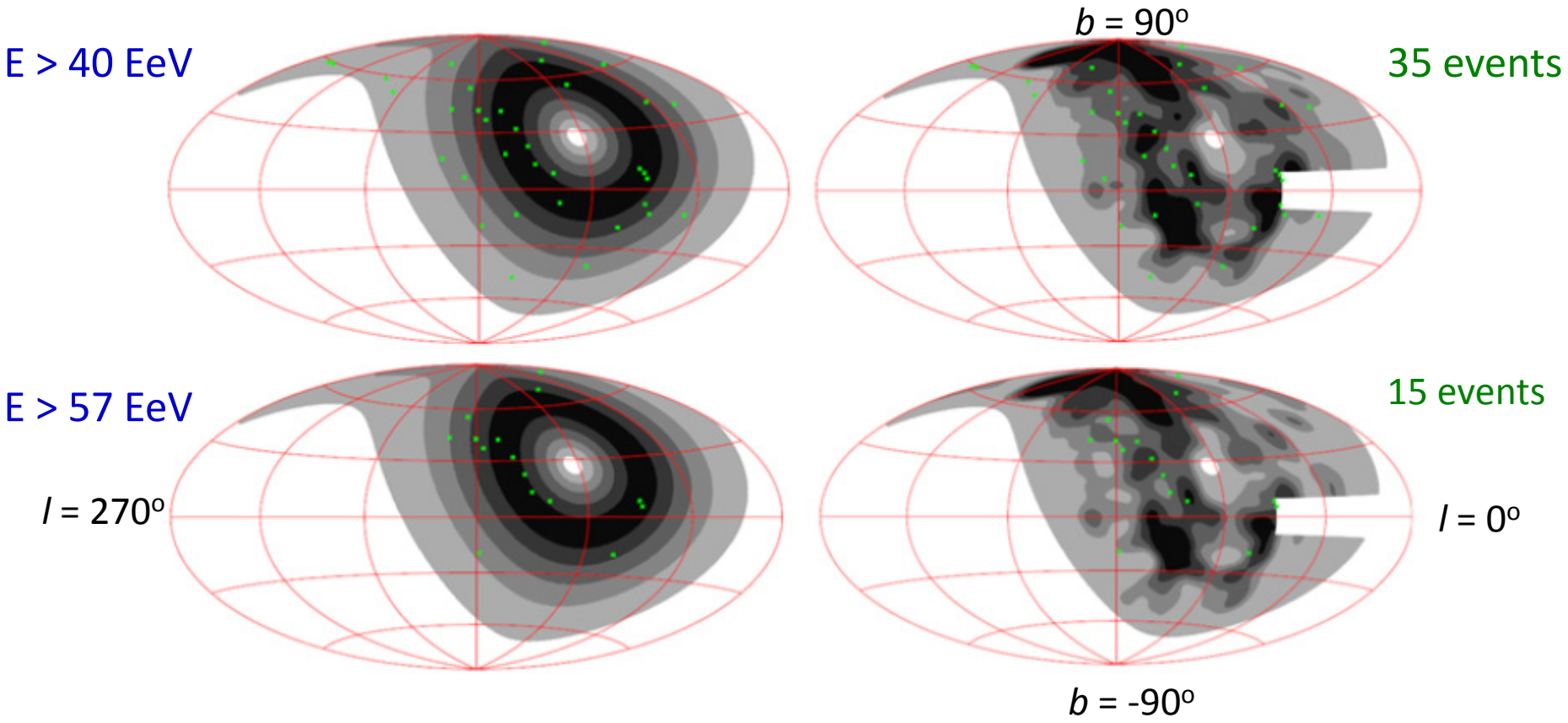
- 2Mass Extended Source (XSCz)
  - m<12.5
  - 5Mpc<D<250Mpc
- Injection spectrum index = -2.4, proton
- Propagation (int. with CMB photon & D^{-2} loss)
- Smearing angle (free parameter)
  - Galactic Magnetic Field (GMF) + extragalactic magnetic field

Flux maps overlaid with data

Data set: SD events from 2008/May to 2010/Sep

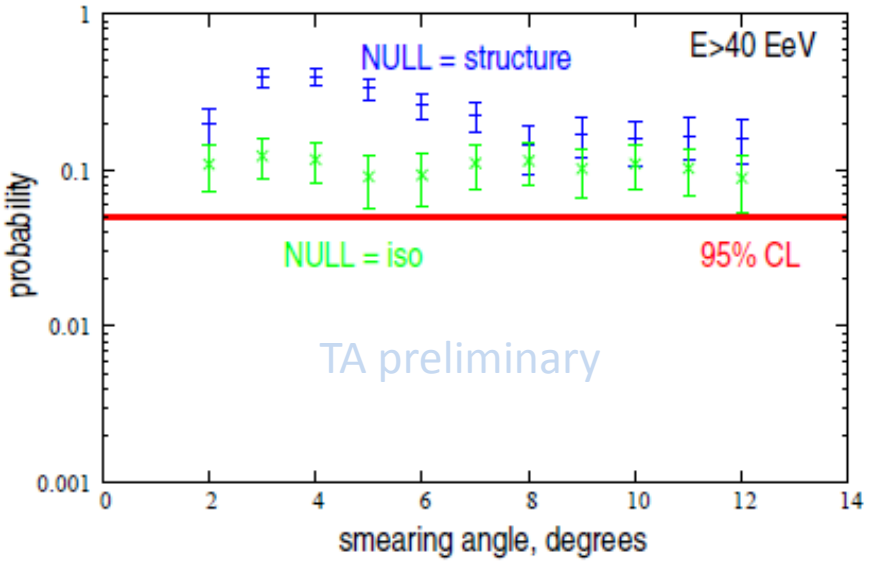
Isotropic model

LSS model (smearing angle = 6°)

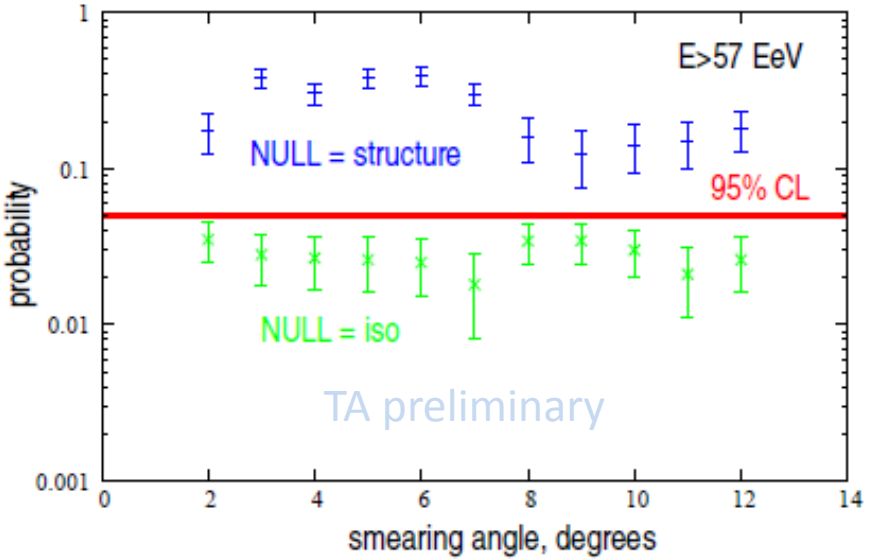


the galactic coordinates

Result

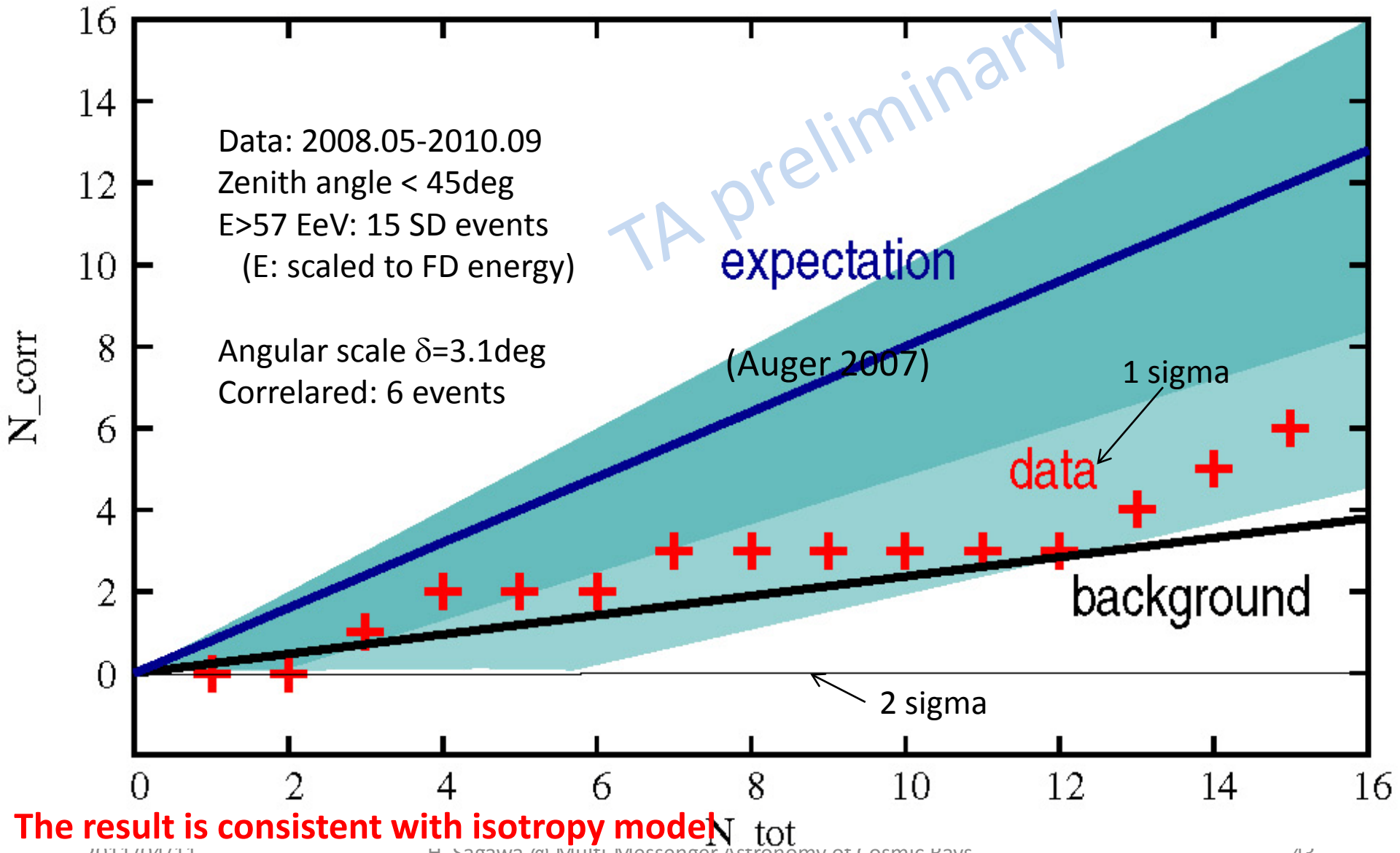


Data with E > 40 EeV is compatible with LSS and isotropy models.



Data with E > 57 EeV is compatible with LSS model, and is not compatible with isotropic model at 95% CL.

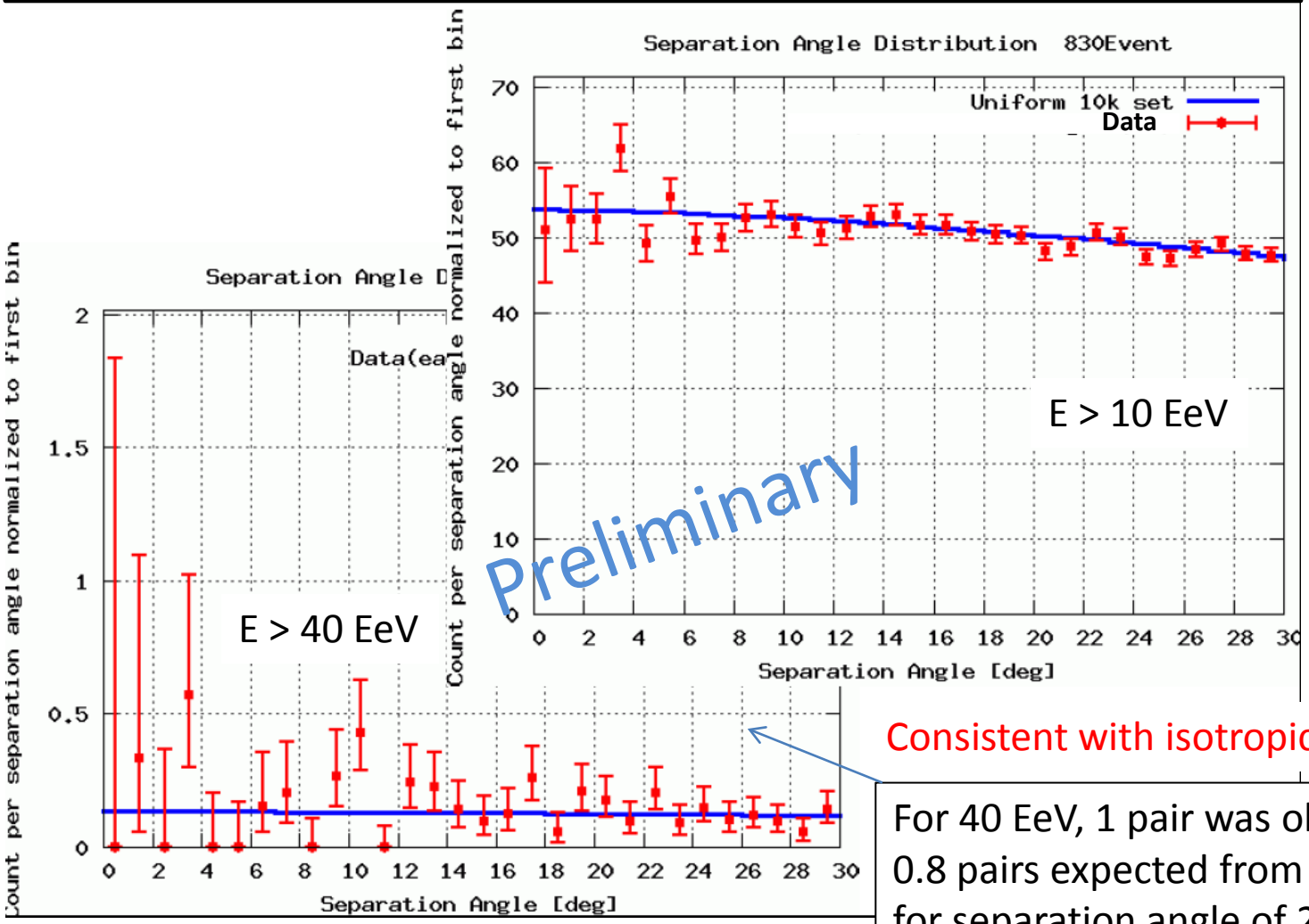
Correlation with AGN



The result is consistent with isotropy model and expectation from Auger AGN correlation.

Autocorrelation

Separation Angle Distribution (normalized by solid angle)



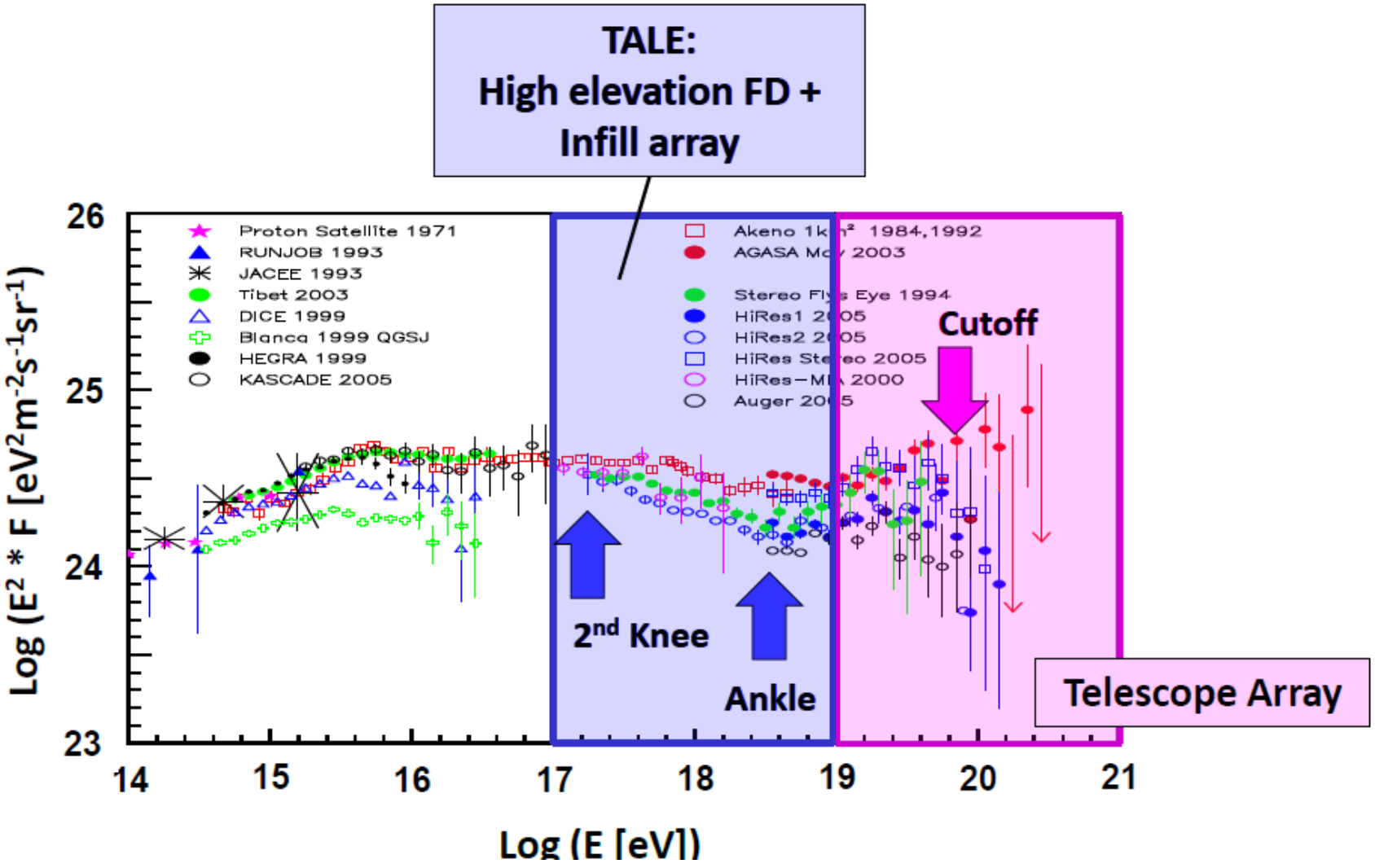
Consistent with isotropic model

For 40 EeV, 1 pair was observed
0.8 pairs expected from isotropy
for separation angle of 2.5°.

Prospects

- TALE (TA Low-energy Extension)
- R&D @ TA site by ELS / UHE cosmic rays
  - Radio detection towards larger ground array
    - Detection by bistatic radar
  - Other possible ideas
    - Detection of microwave bremsstrahlung from UHECRs
    - Test for JEM-EUSO prototype

TALE (TA Low-energy Extension)



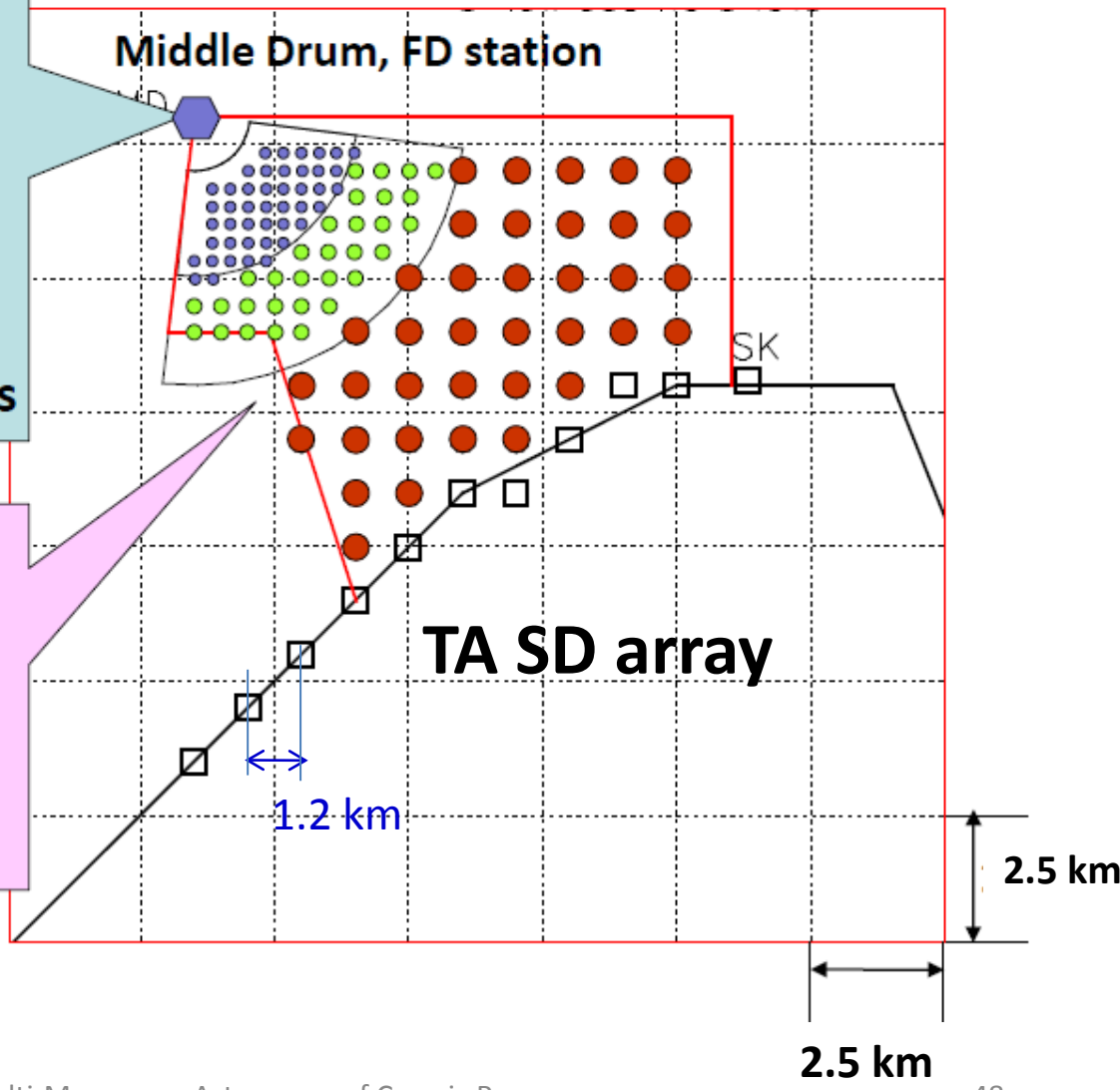
Aim of TALE

- TA+TALE covers ~10^{17} to ~10^{20} eV.
  - ~10^{17}eV: 2nd knee
    - Transition of Galactic CRs to extragalactic CRs?
  - ~$10^{18.5}$ eV: ankle
    - Transition of Galactic CRs to extragalactic CRs?
    - e^+e^- pair creation?
  - ~$10^{19.8}$ eV
    - Cutoff or heavy primary CRs?
- Cross-calibration by different types of detector
  - SD vs. FD
  - Stereo FD, hybrid
  - Energy calibration with ELS (Electron Light Source)

Layout of TALE

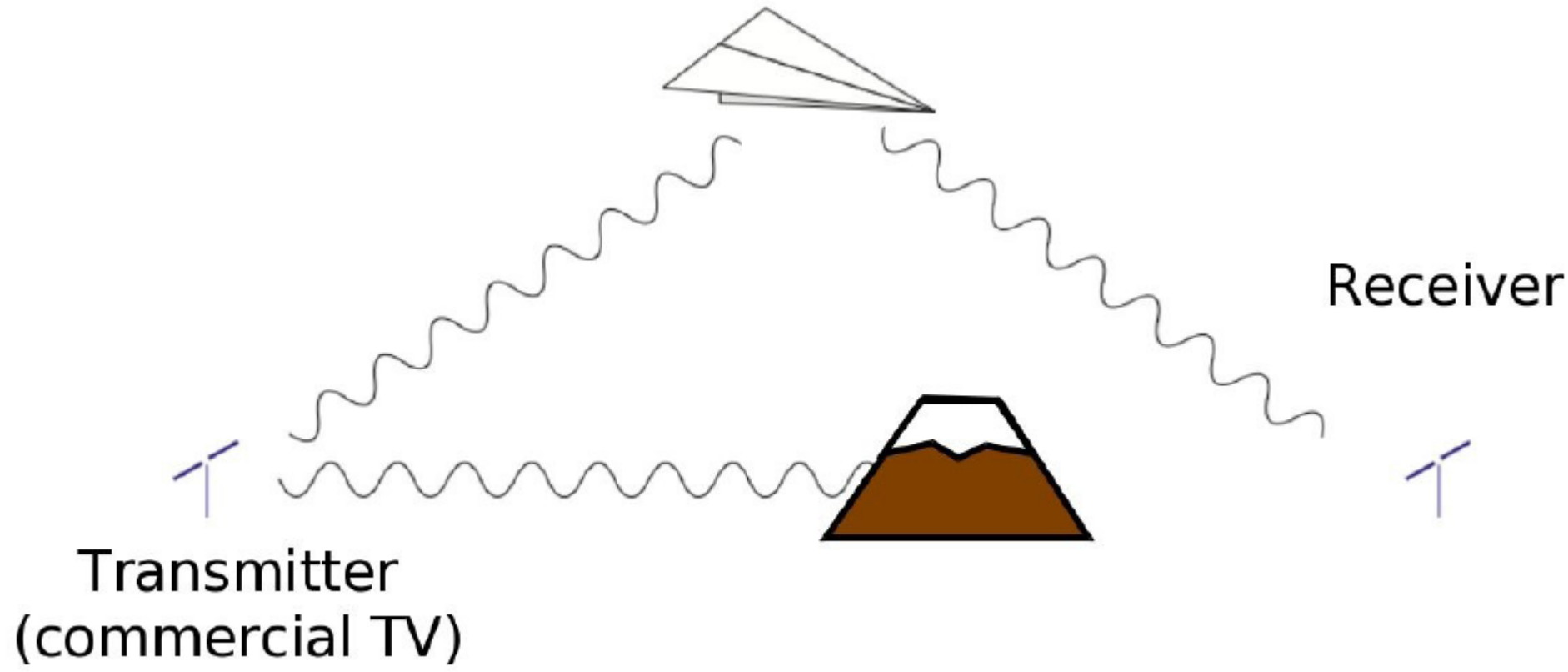
Extend FD field of view @MD :
Add 11 telescopes to MD
→Cover 3° - 59° in elevation
90° in azimuth
HiRes-2 mirrors,
Reconditioned HiRes-2 electronics

113 new SD counters:
45 at 400m spacing, r<3km
31 at 600m spacing, r>3km
37 to build up from main SD array, at 1200m spacing

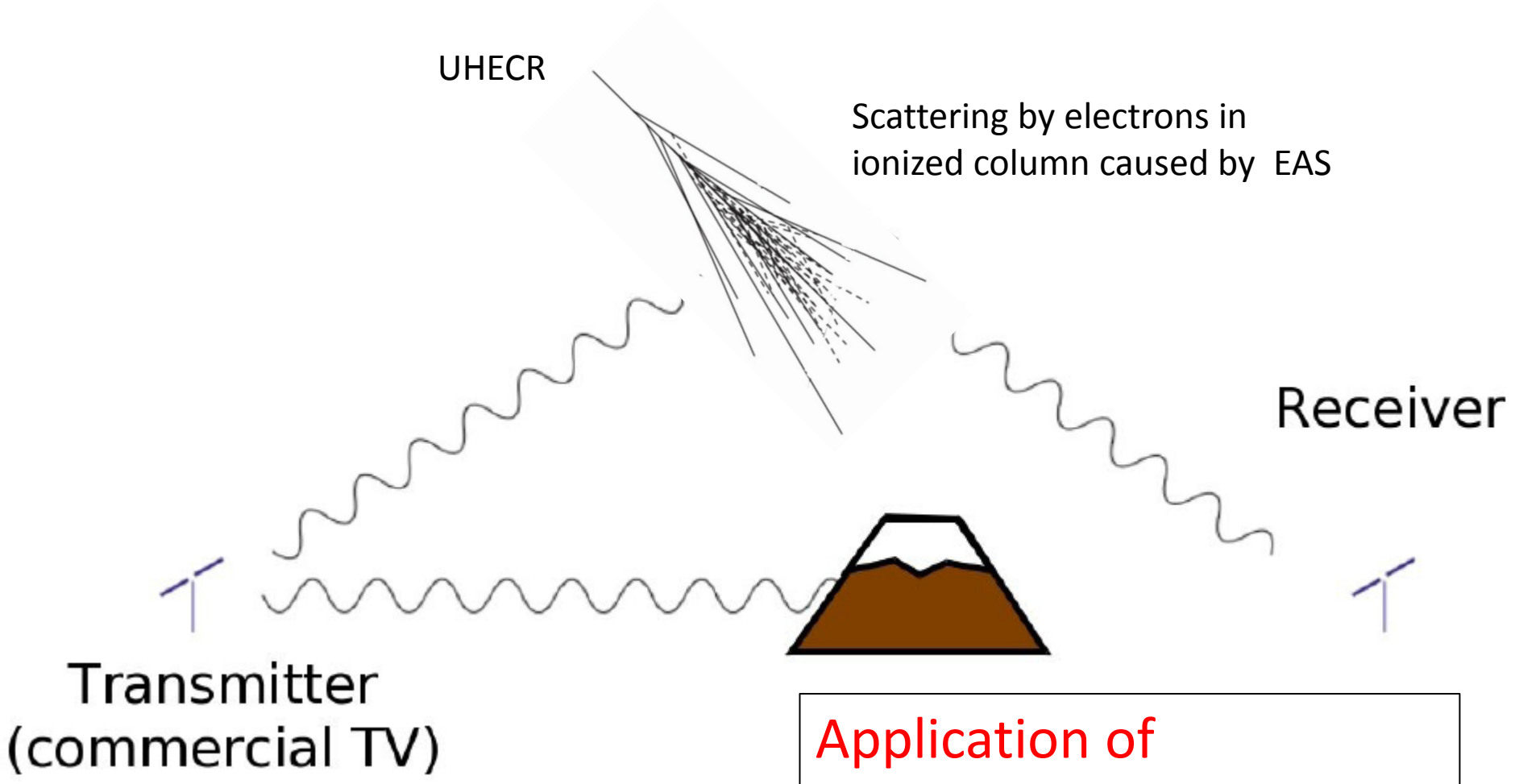


Detection of UHECRs by bistatic radar

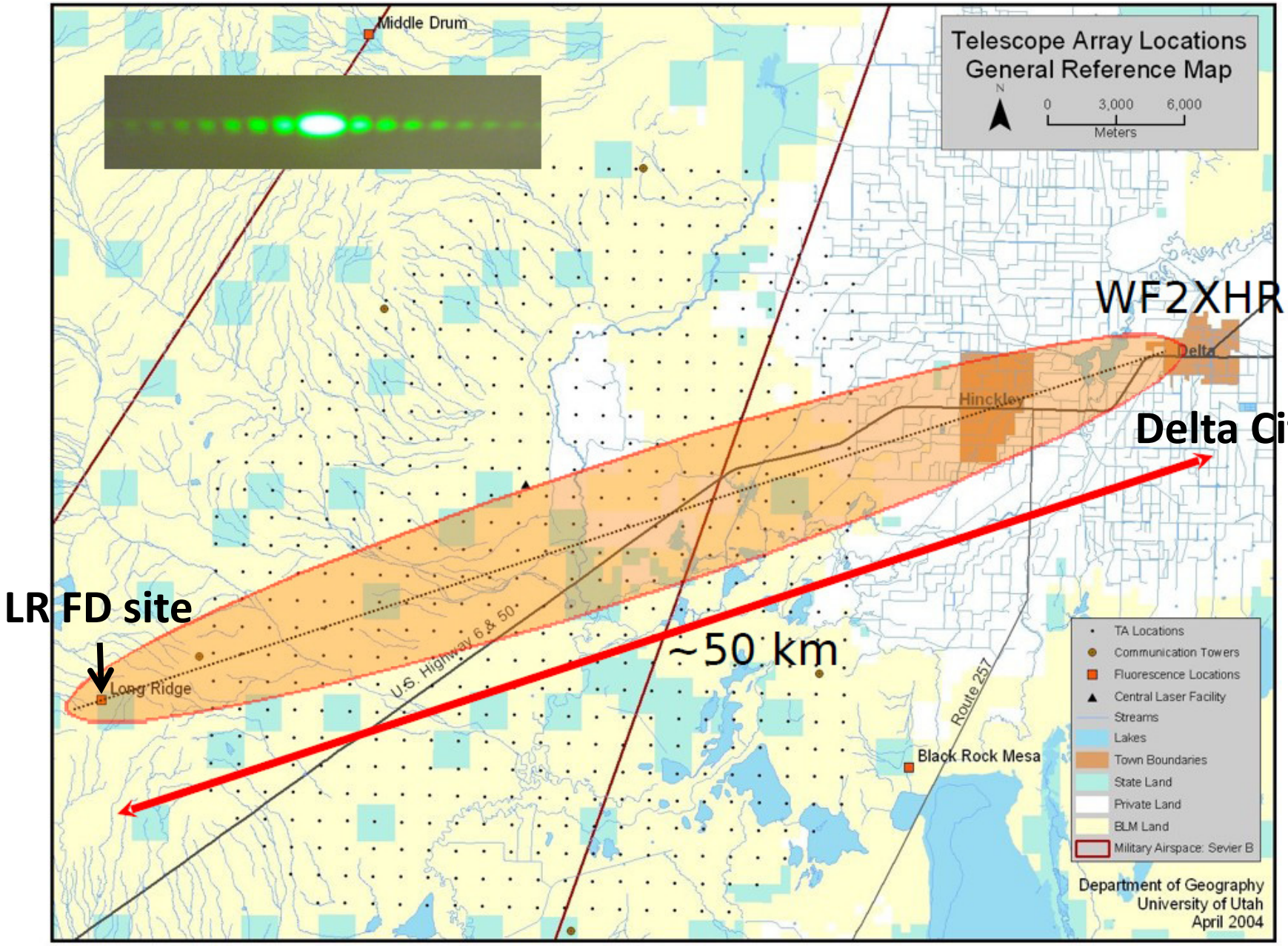
bistatic radar

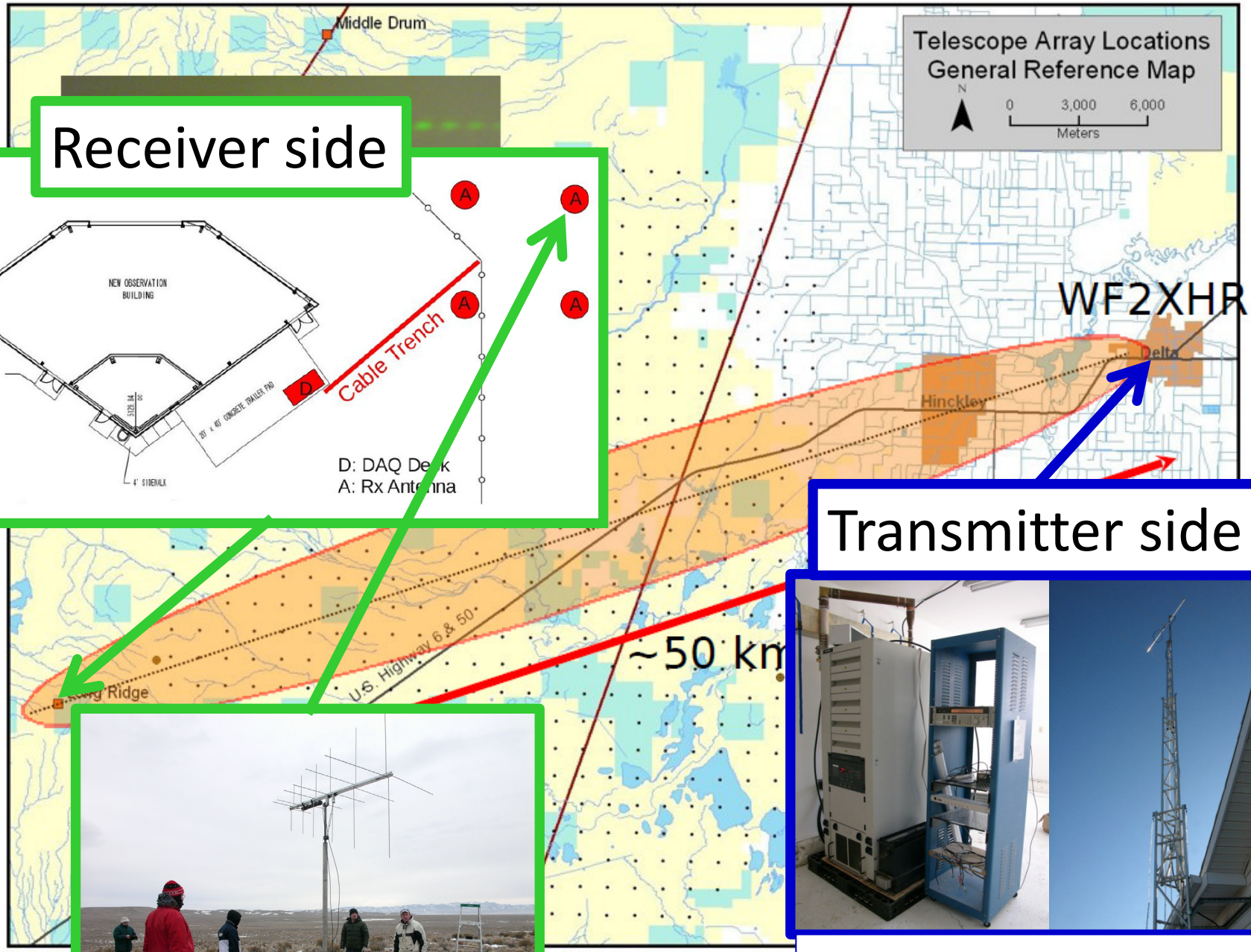


bistatic radar



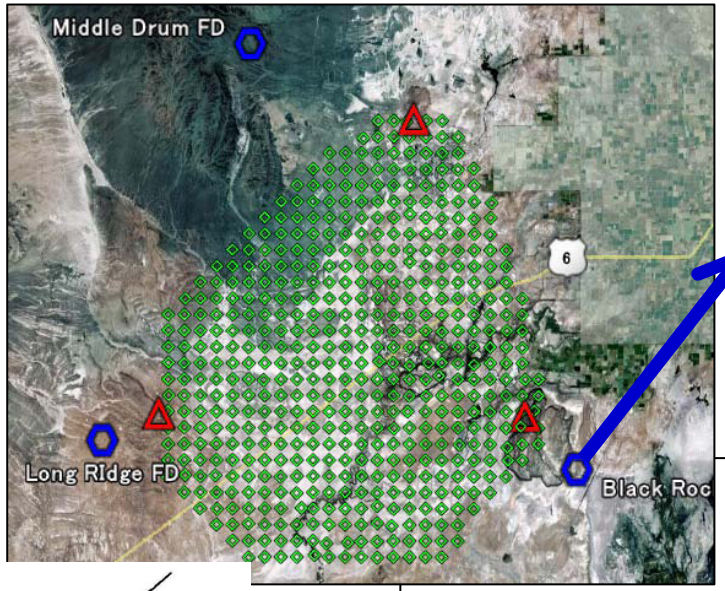
Application of
detection of meteor echo

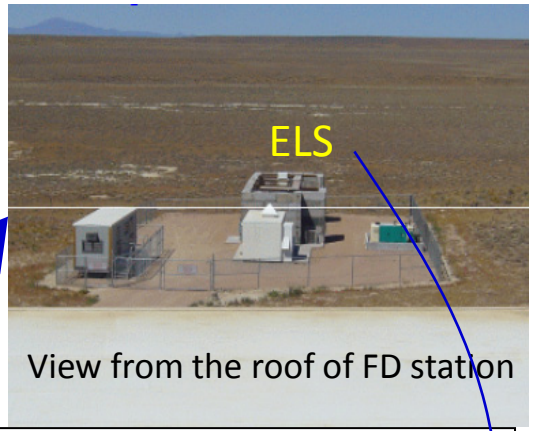

Middle Drum
Telescope Array Locations
General Reference Map
N
0
3,000
6,000
Meters
WF2XHR
Delta
Hinckley
Delta City
LR FD site
Long Ridge
U.S. Highway 6 & 50
~50 km
Route 257
Black Rock Mesa
TA Locations
Communication Towers
Fluorescence Locations
Central Laser Facility
Streams
Lakes
Town Boundaries
State Land
Private Land
BLM Land
Military Airspace: Sevier B
Department of Geography
University of Utah
April 2004


Middle Drum
Telescope Array Locations
General Reference Map
N
0
3,000
6,000
Meters
Receiver side
NEW OBSERVATION BUILDING
Cable Trench
D
A
A
A
A
D: DAQ Desk
A: Rx Antenna
WF2XHR
Delta
Hinckley
~50 km
U.S. Highway 6 & 50
Transmitter side
Transmitter unit
antenna

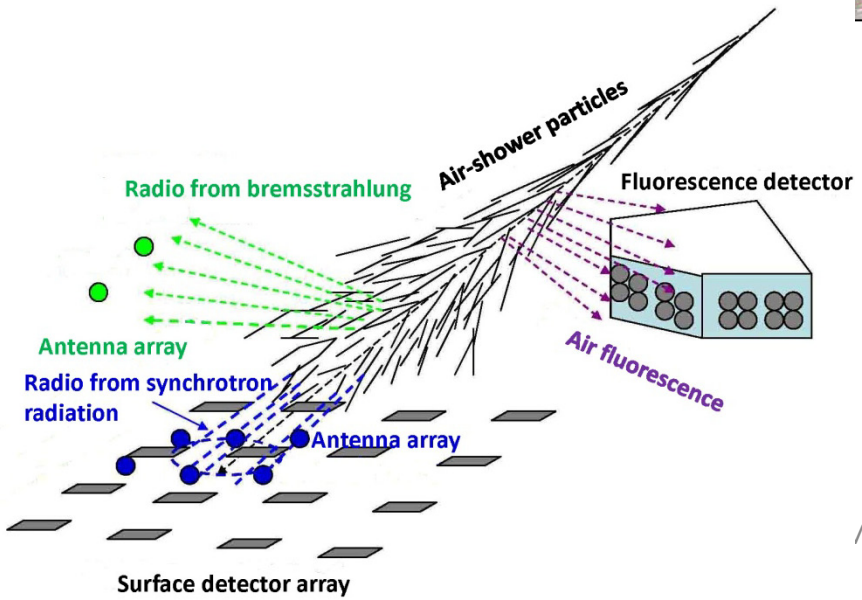
Other possible ideas

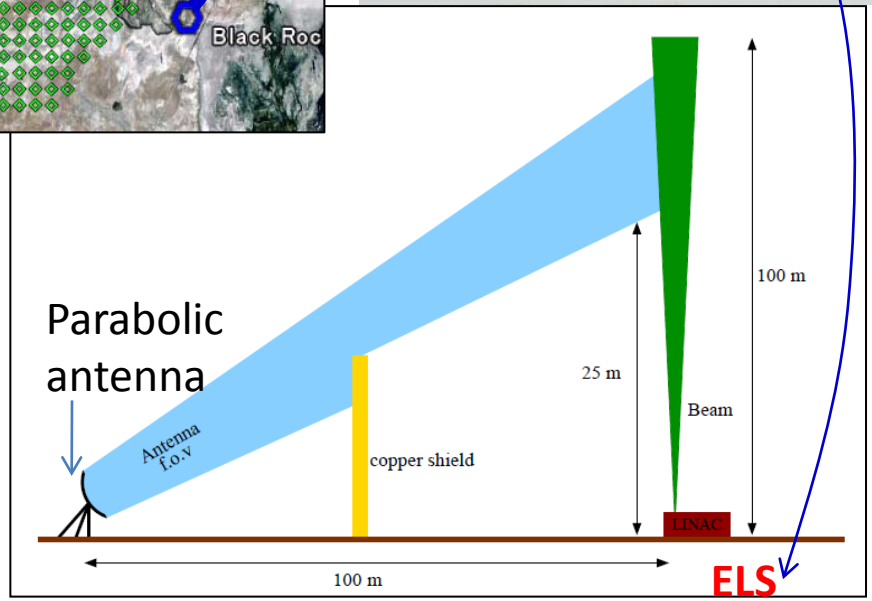
Detection of microwave bremsstrahlung from UHECRs



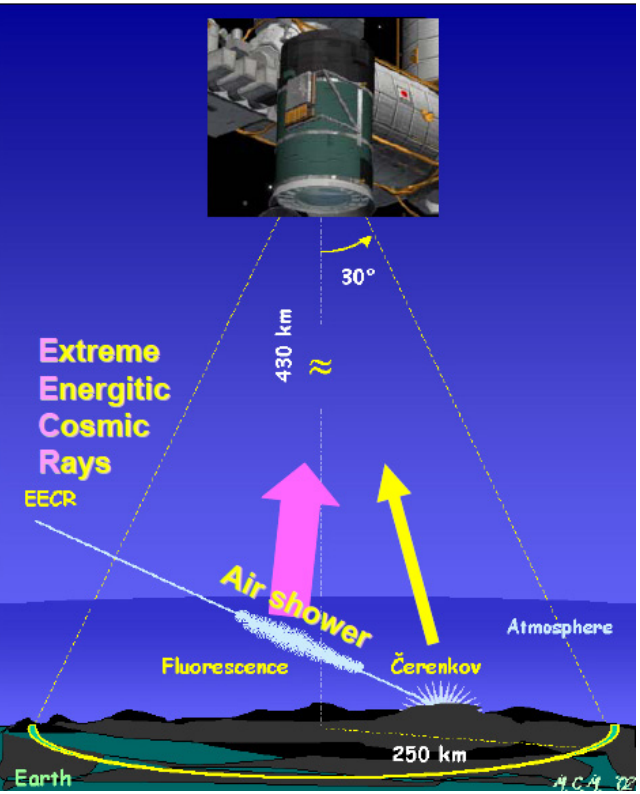


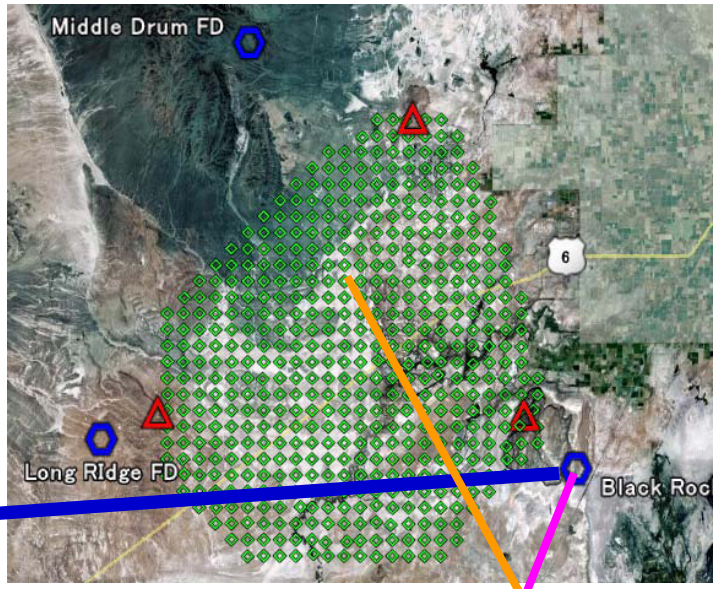
View from the roof of FD station

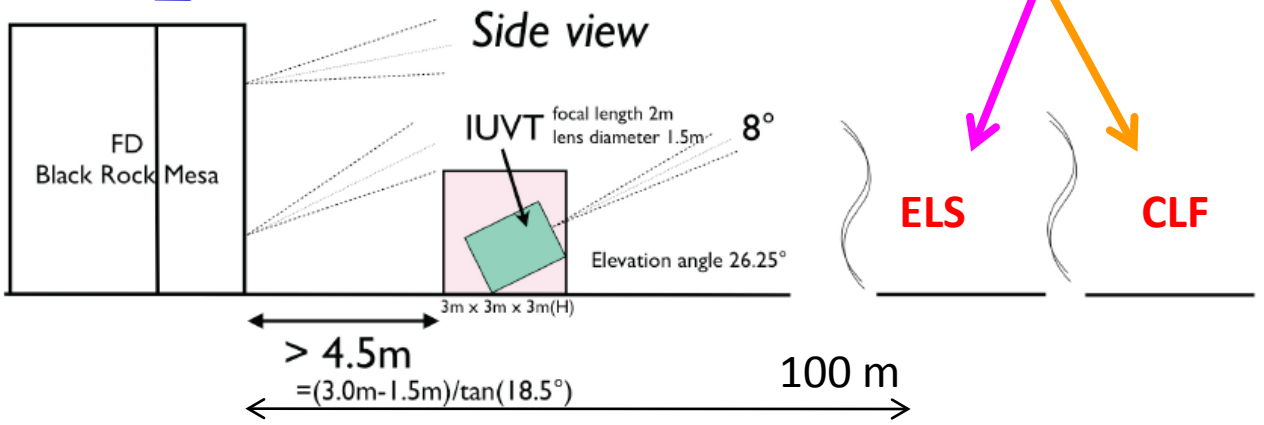




Test of JEM-EUSO prototype







Summary

- Spectrum (hybrid, SD, MD FD mono):
  - Consistent with each other and HiRes-1,2
  - Evidence for suppression (from SD) [3.5σ]
- Mass composition by Xmax analysis: FD stereo
  - consistent with proton prediction
- Anisotropy:
  - LSS: consistent with both LSS and isotropy (E>40EeV)
    consistent with LSS and incompatible with isotropy at 95% CL (E>57 EeV)
  - AGN: consistent to isotropy for E>57 EeV
  - Small scale cluster: consistent with isotropy both for E>10 EeV and E>40 EeV
- Prospect
  - TALE, and R&D or tests for future large-scale UHECR detection is being prepared.